Congressional Testimony

Committee on Science, Space, and Technology
Subcommittee on Energy
U.S. House of Representatives

June 15, 2016

Dr. Nathan S. Lewis, California Institute of Technology

Mr. Chairman and Members of the Subcommittee:

Thank you for the opportunity to discuss the exciting and timely research opportunities in artificial photosynthesis—the direct production of fuels from sunlight.

Artificial photosynthesis has the potential to be a game-changing energy technology, cost-effectively producing fuels that are compatible with our existing infrastructure, and providing both energy and environmental security to our nation.

Artificial photosynthesis is inspired by plants, except that it can be over 10 times more efficient than natural photosynthesis, avoiding the need to trade food for fuel, while producing a fuel that we can directly use in our existing infrastructure, such as gasoline, diesel, methanol, or producing hydrogen that can be converted with nitrogen in the air into ammonia for use as agricultural fertilizer, as well as for other uses as they may develop.

Solar fuels production would allow for massive grid-scale energy storage, and for carbon-neutral transportation fuels, both of which are critical gaps at present towards reaching a full carbon-neutral energy system.

Artificial photosynthesis does not look like a leaf, nor does it look like a solar panel. Instead imagine a high performance fabric that can be rolled out like artificial turf, supplied with sunlight, water, and perhaps other feedstocks in the air such as nitrogen and/or carbon dioxide, and produces a fuel that is wicked out into drainage pipes and collected for use.

Many approaches to solar fuels generators are being pursued. Some are taking biological molecules like chlorophylls, and using them in artificial systems coupled to man-made catalysts for fuel production. Others are using all inorganic materials such as semiconductors like those used in solar panels and coupling them to catalysts like those used in fuel cells. Still others are using metal complexes as dyes to absorb the light and coupling the energy to molecular catalysts to produce the desired fuels.

Laboratories like mine at Caltech have already demonstrated functional solar fuels systems, through advances in nanoscience that have enabled the fabrication of nanofibers of semiconductors that can absorb sunlight and coupled them to catalysts that can seamlessly produce fuel in one integrated assembly. We thus know that this is possible, but we need to continue to innovate and perform fundamental research on such systems to make it practical.

A full solar fuels system needs five components; two materials to absorb sunlight, one to capture the blue part of the spectrum and the other to capture the red part of the spectrum, two catalysts, one to make oxygen from water and the other make the fuel; and a membrane to ensure safe and efficient operation. We have all of these pieces, but do not yet have them all working together in a system that is simultaneously cost-effective, safe, efficient and stable.

Research opportunities include the use of high performance computation to design new fuel-producing catalysts that are both stable and inexpensive; development of new semiconducting materials using nanoscience and materials science to absorb the sunlight at the needed wavelengths; and use of modeling and simulation methods to design a system that will be safe, scalable, and efficient. Although challenging, we are making great progress, and more will be enabled by leveraging the expertise of interdisciplinary teams of scientists and engineers to focus on this use-inspired research area.

Many scientific approaches to solar fuels production are promising and should be pursued in parallel at this early stage of the field. Similarly, many types of solar fuels can be produced, including gases and liquids, hydrogen, methanol, methane, and gasoline. Since fuels can readily be interconverted, all options should be pursued in parallel to determine which are the most technically feasible and promising for implementation. The key is producing a fuel from the sun, and it is not nearly as important which fuel that is, because we can always convert one fuel into another as needed for end-use.

Within the past few years, other countries, including Korea, Japan, China, Sweden, Germany, and the European Union as a whole, have each launched burgeoning research programs in solar fuels. We can beneficially leverage these international efforts, but need to stay in the lead domestically on the research front. We are well-positioned to do this, given our historical leadership in the solar fuels area.

Solar fuels research offers an intellectual challenge to our young scientists such as graduate students and post-doctoral fellows, because it simultaneously involves frontier research challenges in nanoscience, materials science, applied physics, chemistry, and chemical engineering. It is a wonderful focal point for use-inspired, cross-disciplinary research, because the prize is so great. Moreover, the need for fundamental research is compelling, and challenges our scientists and engineers to apply their talents to discovering and designing the new molecules, materials, and systems that will make solar fuels and artificial photosynthesis a reality, and ultimately an option at scale for sustainable fuel production globally. Humans were inspired by biology to fly, but we don’t build airplanes out of feathers, and airplanes fly faster and farther than any bird. Similarly, we are poised to beat nature at its own game: through artificial photosynthesis, we can harness the biggest energy source known to mankind, the Sun, and convert its energy efficiently into a storable, dense form, namely into chemical fuels. Through research we can develop technology that can provide better energy options than those that we have now available, insuring a safe and secure energy future domestically and internationally.

SOLAR FUELS RESEARCH

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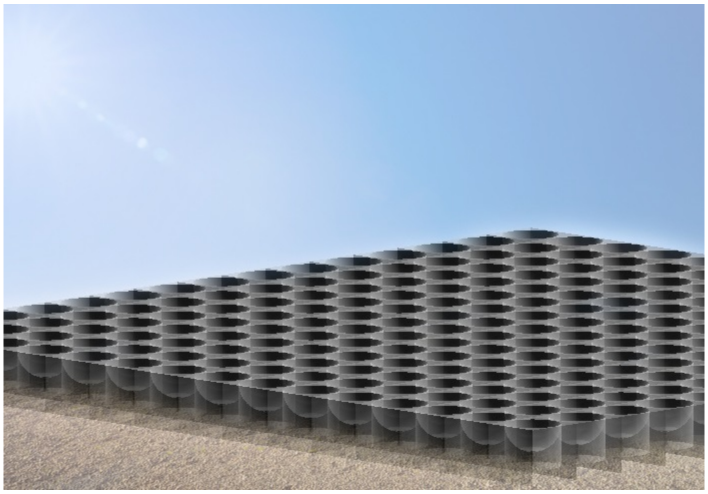
How Does The Lewis Group Approach Making Fuels from Sunlight?

In order to radically reduce the costs of making fuels from sunlight, we focus on developing single-step devices from Earth-abundant elements, using techniques which minimize the total costs of materials without compromising on efficiency or safety. Since capital costs – for example labor, wiring, and equipment – need to be reduced significantly for solar fuels to be cost-competitive with fossil fuels, we focus on an architecture compatible with flexible materials, and envision a system that can be installed simply, like unrolling bubble wrap or artificial turf.

What Might a Solar Fuels Device Look Like?

We are designing systems that can make fuels from sunlight efficiently and safely. We use modeling and simulation tools to evaluate device designs so that we understand the theoretical limits to the design, and so



Bubble-wrap design for a solar fuels device, consisting of plastic cells that concentrate sunlight, with each cell containing a small active component (semiconductors, catalysts, and membranes) and water.

that we understand which parameters have the greatest impact on performance. Much of this modeling is done in collaboration with the team of Chengxiang Xiang, a Lewis Group alumnus and a Principal Investigator with the Joint Center for Artificial Photosynthesis.

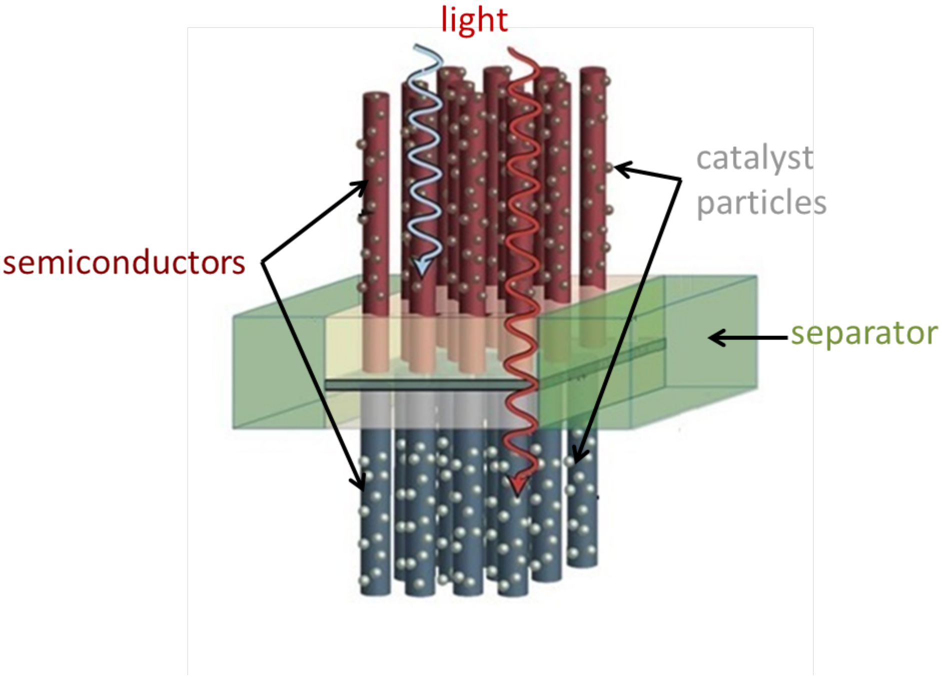
The bubble-wrap design sketched on this page consists of an array of plastic cells, each of which contains a small active component and water. This design uses simple, inexpensive plastic lenses to concentrate sunlight, and therefore allows a ten-fold reduction in the materials used for the active components relative to the materials requirements for devices without concentrating lenses. Since most of the design is plastic, the materials costs would be low, and the structure would be flexible, allowing it to be rolled out like bubble wrap or artificial turf, radically reducing installation costs relative to current solar fuels technologies. Other designs, for example an array of long cells based on trough-shaped plastic lenses, would achieve comparable efficiency while reducing materials and installation costs.

The optimal designs (on cost and efficiency metrics) vary depending on whether the device makes hydrogen from sunlight and water or carbon-based fuels from carbon dioxide, water, and sunlight. Devices designed to produce hydrogen fuel typically contain either acidic or alkaline water, while those designed to produce carbon-based fuels typically contain water buffered with carbonate salts. Some designs allow cells to fed either by humidified air, or by humidified deoxygenated air.

The active components of a solar fuels device are light absorbers and catalysts. For safety and efficiency purposes, solar fuels devices also need separators to prevent mixing of the chemical products of the reaction (fuels and oxygen).

Read more about devices in the Lewis Group Research pages.

What Might the Active Components Look Like?



We envision active components consisting of wire-shaped semiconductors that are decorated with catalyst particles and embedded within a separator.

Semiconductors

The function of the semiconductors is to absorb sunlight and convert the energy in the absorbed sunlight into the potential energy of separated positive and negative charges.

Since sunlight is multispectral – it contains a wide range of energies (higher energies for violet and blue, lower energies for red) – we envision two complementary semiconductors, one on top which absorbs only higher energy light, and the other on the bottom to absorb any light which passes through the top (lower energies).

We can use silicon as the bottom absorber, but we are looking for a semiconductor for the top absorber that will not corrode and that can be made inexpensively from Earth-abundant elements.

Read more about semiconductors in the Lewis Group Research pages.

Catalysts

The active component needs two catalysts: one for the chemical reaction that yields fuels, and the other for the chemical reaction that yields oxygen gas. The reaction that forms oxygen gas is a necessary partner to the fuel-forming reaction, providing the electronic charges needed for the fuel-forming reaction, and closing a combustion-based fuel cycle.

Without catalysts, these reactions would proceed very slowly (if at all). Although the reactions are thermodynamically favored under the operating conditions in a solar fuels device, the reactions first need an uphill push – for example, electronic charges and molecules need to get close enough to react. Catalysts increase the reaction rates by decreasing the height of the hill.

Catalysts used in devices which make fuels from sunlight need long-term stability, preferably decades of stability under operating conditions. The catalysts need to attach firmly to the semiconductors, and can't dissolve, corrode, or undergo any other chemical reactions that would reduce their effectiveness. Stable catalysts are often based on expensive and rare elements – platinum, iridium, ruthenium and rhodium are a few examples. We are looking for catalysts based on Earth-abundant elements, such as nickel, iron, cobalt, or zinc. Ideally the catalysts would be transparent to sunlight, so that they don't block light from reaching the semiconductors; however, we have developed strategies for catalyst placement and loading that would considerably reduce the amount of light blocked by an opaque catalyst.

Several catalysts based on Earth-abundant elements and capable of making hydrogen fuel from water have been discovered as a result of solar fuels research. This set of catalysts – transition metal phosphides and nickel-molybdenum – offers options for stability and efficiency for either acidic or alkaline water. We also have catalysts – nickel-iron oxide and cobalt oxide – that offer stability and efficiency for making oxygen from alkaline water.

We are looking for catalysts that can make carbon-based fuels from carbon dioxide and water. We are also looking for catalysts that can make oxygen from acidic water. We collaborate with Professor Ray Schaak at the Pennsylvania State University for many of our catalyst-discovery efforts.

Read more about catalysts in the Lewis Group Research pages.

Separators

Separators are critical components in a solar fuels device. For safety reasons, separators must prevent the fuels and oxygen formed by solar fuels devices from mixing in the cell or in the output streams. In order for the devices to function, separators must also allow ionic current to pass.

Without a separator ionic current would pass, but the products (fuels and oxygen) would not readily be separated. If fuels and oxygen are not separated everywhere and all the time: 1) The products from desired chemical reactions – fuels and oxygen – will recombine yielding the starting materials while releasing, possibly explosively, the energy of sunlight that was stored as chemical bonds; and, 2) Reverse chemical reactions will occur that convert fuels back to water (and carbon dioxide for carbon-based fuels) and that convert oxygen back to water, wasting the energy from sunlight that had been stored in the chemical bonds of the fuel.

Where Can I Get More Information on Solar Fuels Research?

- Check out Who is Making Fuels from Sunlight?
- Check out the Lewis Group Research pages.

- Read “Research Opportunities to Advance Solar Energy Utilization” published in *Science* (volume 351, 2016) and written by Prof. Nate Lewis.
- Read “Will Solar-Driven Water-Splitting Devices See the Light of Day” published in Chemistry of Materials (volume 26, 2014, pages 407–414) and written by Lewis Group alumnus James McKone, Prof. Harry Gray, and Prof. Nate Lewis.

by Kimberly Papadantonakis, June 2016.

More energy from the Sun hits the Earth in one hour than humans use in an entire year

Why Make Fuels from Sunlight?

Solar is by far the most abundant source of renewable energy available on Earth.

However, the sun is an intermittent and variable resource at any given location on the Earth's surface. Therefore, a reliable energy system in which solar plays a significant role will require a way to store the energy captured from sunlight so that it will be available upon demand, at any time of day or year.

Making fuels from sunlight would store solar energy so it can be used on demand at any time of the day (or night).

The chemical bonds found in fuels are the most dense way to store energy outside of an atomic nucleus. For example, the energy density of gasoline is 60 times that of the best battery. In other words, 60 tons of batteries would be needed to store the energy contained in 1 ton of gasoline.

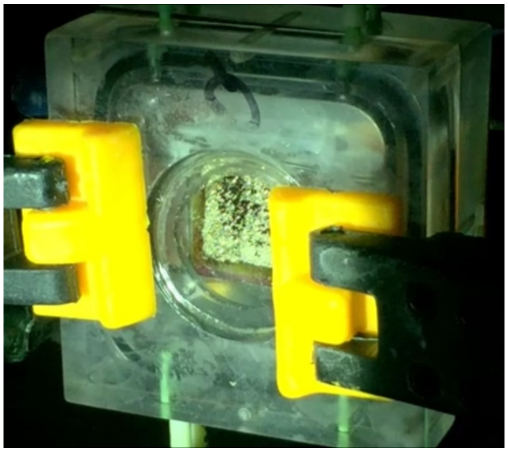
Fuels made from sunlight would:

1. Provide the massive grid-scale energy storage that is needed to compensate for the intermittency of solar power;
2. Provide an abundant source of the liquid fuels that are needed to power heavy-duty trucks, ships, and aircraft. Together these vehicles currently use ~40% of transportation fuels globally, and demand and will grow further as global commerce expands especially in developing nations. Unlike automobiles, these vehicles cannot run on batteries alone.

Airplanes, ships, and heavy-duty trucks cannot run on batteries alone and require energy-dense fuels.

What is Solar Fuels Technology?

Solar fuels technologies are developmental systems that use robust, cheap, and highly efficient components to produce fuels that can readily be used in our existing energy infrastructure. Solar fuels technologies use sunlight, water, carbon dioxide, and nitrogen from the air to produce fuels. Solar fuels are sustainable and produce no net emissions of carbon dioxide.


An example of solar fuels technology. Oxygen gas bubbles form at the center of the front of this water-containing cell when it is illuminated, and bubbles of hydrogen fuel form and are collected at the back of the cell.[1]

Solar fuels technologies are analogous to natural photosynthesis – plants make fuels (biomass) from sunlight.   However, the fastest growing crops store <1% of the sunlight they receive as biomass. In order to be compatible with our energy infrastructure, the primary biomass made by plants – lignocelluose – must be converted into ethanol, biodiesel, or gasoline. This conversion requires energy and labor. Converting crops to fuels raises significant land-use concerns, specifically with regard to trading food for fuel.

We could make a fuel – hydrogen gas – from sunlight simply by pumping electricity from solar panels into water. This process is called water electrolysis, and making solar fuels this way would use two proven technologies: solar panels and electrolyzers. Although mature, both of these technologies remain expensive, and the hydrogen that would be produced this way would be prohibitively costly when compared to hydrogen as it is currently produced at large scale from natural gas. Furthermore, commercial electrolyzers typically use precious metal catalysts (e.g., platinum and iridium), which imposes a barrier to scaling this technology globally.

What Fuels Can Be Made From Sunlight?

The Lewis Group leads the development of solar fuels technologies that produce hydrogen gas directly from sunlight and water. Carbon-containing fuels such as natural gas (methane) or liquid fuels such as methanol or ethanol might be produced from sunlight, water, and carbon dioxide. Ammonia for use as fertilizer in agriculture can be made indirectly from solar hydrogen or directly as a solar fuel from sunlight, water, and nitrogen in the air. Fuels can be readily interconverted using well-known processes implemented in petrochemical refineries.

Solar fuels would provide the same quality and quantity of energy services that end-users are used to, without a massive change in infrastructure, and hence would produce “drop-in” fuels that could serve critical sectors of the energy economy both in the developed and developing world. The feedstocks for solar fuels are abundant: sunlight, water, carbon dioxide, and nitrogen from the air. Solar fuels are sustainable and produce no net carbon dioxide emissions.

Are Solar Fuels Technologies Ready for Commercialization?

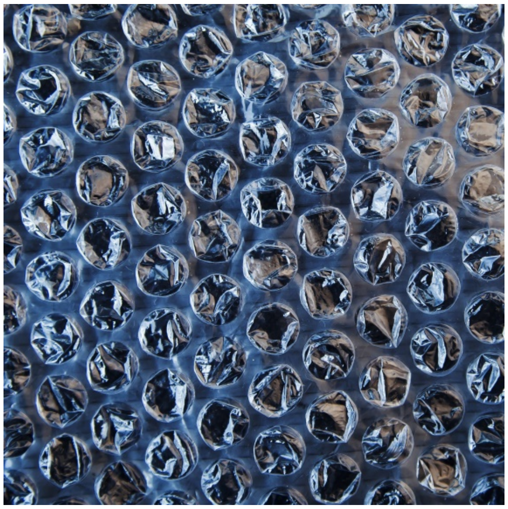
Solar fuels technologies are developmental systems that are not yet ready for commercialization. Although a number of prototypes have been demonstrated, they can't now compete with existing energy technologies, and can't yet provide the long-term (20 years) stability that would be needed.

What are the Key Hurdles?

The key hurdles to making fuels from sunlight commercially are:

1. Cost competitiveness – Using current technologies, hydrogen made from sunlight would cost about ten times more than hydrogen made from fossil fuels. The high cost of solar fuels is primarily driven by costs such as labor, wiring, equipment, and materials for mounting solar panels.
2. Materials discovery and system design – Because fuels made from sunlight using current technologies would cost so much more than fossil fuels, radically new materials and system designs, that can be installed simply and at low costs, are needed.

What are Scientists Doing to Overcome the Hurdles?


One radically new design for a solar fuels technology looks like bubble wrap, so it would be easy (and cheap) to make and install.

Several approaches are being pursued to construct a demonstration solar fuels system. In one approach, the molecular components of natural photosynthesis, such as chlorophylls, are synthesized and modified chemically to attempt to construct a complete, functional photosynthetic system in the absence of a living organism such as a plant or photosynthetic bacteria or algae. In another approach, inorganic molecules, such as transition metal complexes, are used instead of chlorophylls as the light absorbers, and these complees are either coupled chemically to biological catalysts or are coupled to inorganic catalysts, such as metallic colloids or particles to generate solar fuels. In yet another approach, metal dyes are bonded to titania films to absorb light, and the dyes are also chemically are coupled to transition metal catalysts to produce solar fuels. Inorganic semiconductors, similar to the ones used in solar panels, can also be used either indirectly to produce electricity in conjunction with catalysts for solar fuels production, or can be used as photoelectrodes to directly produce fuels from sunlight. All of the approaches have their own advantages and challenges both from a technical and cost perspective, requiring further materials discovery and research to address.

The Lewis Group, along with our partners and other scientists and organizations, is pursuing radically new designs that would make fuels from sunlight at a fraction of the price of the best solar fuels technologies (solar panels and electrolyzers) currently available. The key idea behind the new designs is combining the functions of solar panels and electrolyzers – conversion of light to electricity, followed by conversion of electricity to hydrogen – into a single, one-step process that would produce fuels directly from sunlight, resulting in simpler systems with low installation and materials costs, and therefore much lower costs for solar fuels.

However, reaching low enough costs by combining these functions requires intimate contact between the materials that convert light to electricity (semiconductors) with the strongly corrosive environment needed for an efficient electrolyzer. This causes semiconductors to corrode rapidly and to stop working. To address this problem, the Lewis Group is looking for new or non-traditional semiconductors that are stable in corrosive environments and is developing protective coatings that prevent the corrosion of semiconductors.

Common forms of commercial electrolyzers depend on expensive and scarce elements – platinum and iridium – to catalyze chemical reactions. The Lewis Group is discovering inexpensive materials – made from elements plentiful on Earth such as nickel, cobalt, and phosphorous – to replace these catalysts without reducing efficiency.

Additionally, scientists don't yet know how to produce carbon-containing fuels – such as natural gas (methane) or liquid fuels (methanol or ethanol) – efficiently from carbon dioxide and water in a solar fuels technology. The Lewis Group is discovering new catalysts to enable the generation of carbon-containing fuels.


A radically new design for a solar fuels technology might be analogous to artificial turf that can be rolled out and inexpensive to make and install.

These challenges are at the frontiers of solar fuels research: discovering new light absorbers to enable efficient, cheap, stable operation; discovering new catalysts to replace expensive materials that seamlessly mate with the light absorbers; discovering suitable membranes to provide for safe operation and to separate the products without introducing an explosion hazard; and insuring that all of the components are mutually compatible and function under the same operating conditions to form a complete system for solar fuels production. High-throughput experimentation, directed materials discovery, advanced computation and theory, and modeling and simulation tools at the system level are key ingredients in a broad solar fuels research program.

Where Can I Get More Information About Making Fuels from Sunlight?

- Check out the Lewis Group Solar Fuels Research page at http://www.nsl.caltech.edu/solar-fuels/solar-fuels/research
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- Check out Who Makes Fuels from Sunlight at http://www.nsl.caltech.edu/who-makes-fuels-from-sunlight

References

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Nathan S. Lewis is a Professor of Chemistry at the California Institute of Technology, Caltech. Dr. Lewis is an inorganic/materials chemist who is a globally recognized authority in artificial photosynthesis. Dr. Lewis has published over 400 papers, was cited over 4000 times in 2015, serves as the principal investigator on energy-related projects sponsored by the National Science Foundation, Department of Defense, and Department of Energy, and has supervised over 60 Ph.D. students who have gone on to careers in energy R&D. Prof. Lewis is the founding Editor-in-Chief of the journal *Energy and Environmental Science*, the leading scientific journal globally in energy R&D, and was named the #17 *Agent of Change in America* (and the top-ranked scientist) by Rolling Stone magazine in 2009, along with receiving numerous honors and awards from scientific and professional societies for his accomplishments.