



Congressional Testimony

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Harry A. Atwater, JCAP Director

SUMMARY

The Joint Center for Artificial Photosynthesis (JCAP) —one of four Department of Energy Innovation Hubs— is building the scientific foundation for a scalable solar-powered technology that converts sunlight, water and carbon dioxide into renewable transportation fuels without added energy, in essence making fuels from sunlight. The development of a renewable fuel source that can meet the nation's energy demand is important to the energy security, environmental protection, and economic well being of the United States. In the first 5 years, JCAP helped design the first robust, stable solar-fuel generators for renewable hydrogen production from water splitting—ten time more efficient than in natural systems. The next five years will be focused on converting carbon dioxide into a transportation fuel.

Like natural photosynthesis, artificial photosynthesis uses light-harvesting structures and catalysts to convert sunlight directly into chemical fuels. JCAP's approach uses designs that incorporate scalable, robust non-biological components and materials, some of which are similar to those used in solar photovoltaic panels.

Established on September 30th, 2010, and renewed by the Department of Energy on September 30th, 2015, for another 5 year term, JCAP is led by the California Institute of Technology and its lead partner, Lawrence Berkeley National Laboratory (LBNL), and draws on the expertise of key partners from the Stanford Linear Accelerator (SLAC), and the University of California campuses at Irvine (UCI), and San Diego (UCSD). The leadership team of Director and Senior/key personnel actively manages the research project as a single integrated organization with primary scientific staff and facilities at Caltech and LBNL

JCAP aims to find a cost-effective method to produce fuels using only sunlight, water, and carbon dioxide as inputs. JCAP's mission is the development of manufacturable solar-fuels generators that robustly produce fuel from the sun, ten times more efficiently than current plants and crops. Achieving this goal requires a Hub-scale program, since scientific discoveries are required in many different fields, including electrochemistry, catalysis, semiconductor science

and polymer physics, and JCAP's integrated Hub effort is designed to overcome basic research challenges in harvesting energy from sunlight and catalytic conversion to chemical fuels. The Fuels from Sunlight Hub is unique since there is no established solar fuels industry. Thus JCAP's scientific discoveries and technology advances are designed to enable future commercial development of solar fuels generators and a future artificial photosynthesis industry.

The scope JCAP's artificial photosynthesis program includes two broad solar fuel objectives: i) production of hydrogen from sunlight and water and ii) synthesis of renewable carbon-based transportation fuels from directly from sunlight, carbon dioxide and water.

In its first five years of operation, JCAP's major research emphasis was on hydrogen production, and several important outcomes were achieved. First, scalable designs for solar fuels generators were conceived, prototyped and tested. Second, new multicomponent earth-abundant catalyst materials were discovered and benchmarked. Third, JCAP prototypes have achieved solar fuel generation with efficiency ten times greater than natural photosynthesis. Fourth, outcomes of JCAP's basic research have pointed the directions for future applied research and development on solar fuels generators.

In its renewal program beginning in 2015, JCAP aims to accelerate progress in synthesis of renewable carbon-based transportation fuels. This goal requires discovery of new materials and basic chemical mechanisms for robust solar-driven carbon dioxide reduction under mild conditions, with efficiency exceeding that of natural photosynthesis, and with comparable selectivity. JCAP renewal is focused on design of catalysts for carbon dioxide reduction whose performance is precisely tuned by control of structure, composition and catalytic environment to generate a desired fuel product or precursor. JCAP will develop foundational prototypes, and will integrate its advances with those made by the broader scientific community to lay the foundation for transportation fuels from carbon dioxide.

JCAP's renewal is an actively managed, milestone-driven program, working from an integrated project plan, that seeks to discover new catalytic mechanisms, materials and components, and evaluate their performance as elements of a solar fuels generator:

a. *Mechanisms*: JCAP researchers are significantly expanding the discovery of scientific concepts and understanding for heterogeneous CO₂ reduction and oxygen evolution catalysis, under both dark and sunlight-illumination conditions, yielding catalysts that are active, stable, and selective to give products such as hydrocarbons and alcohols.

b. *Materials*: Discovery of new materials is being accelerated by use of high-throughput experimentation, a powerful materials discovery capability that automates the synthesis and hierarchical screening of new light harvesting and catalyst materials for solar-fuels generation. These high-speed, combinatorial experimental techniques are paired with new theoretical methods for rapid combinatorial analysis and screening to build a comprehensive database of promising candidate materials, whose performance will be assessed and improved through directed materials research.

c. *Components*: By combining catalysts, light absorber materials, electrolytes, membranes and protective coatings, JCAP is working to realize photocathodes and photoanodes for carbon dioxide reduction and oxygen evolution and evaluate their performance under model and real-world conditions. These components will form the candidate building blocks for a solar-driven solar fuels generator prototype capable of producing carbon-based transportation fuels and form the scientific and technical foundation for a new sustainable fuels technology.

What are the primary research and development goals of JCAP? Since the hub was organized by DOE, what progress has been made towards these goals?

Established on September 30th, 2010, the primary research and development goal for the Joint Center for Artificial Photosynthesis (JCAP) over the last five years has been to realize a scalable solar fuels generator with efficiency at least ten times greater than that for natural photosynthesis. In the last five years, a revolution has occurred in the understanding and development of solar-fuels generators for renewable hydrogen production from water splitting. Since its inception, the Joint Center for Artificial Photosynthesis (JCAP) has played a leading role in this revolution by integrating advances spanning from discovery of catalysts and development of protection coatings for light absorbers, to new system concepts for self-sustaining integrated solar-fuels generators.

Selected Achievements to Date

- JCAP's discoveries and designs for integrated solar-fuels generator prototypes in its first five years have enabled to solar-to-hydrogen efficiency ten times greater than in natural systems.
- This work has set the stage for development of the next generation of integrated water splitting solar-fuels generators with even higher efficiency.
- New earth-abundant catalyst materials for water oxidation and proton reduction were discovered.
- A new method to protect semiconductors from corrosion was discovered, greatly expanding the range of candidate materials usable in solar fuel generators.
- 2 state-of-the-art laboratory buildings, purpose-built for solar fuels research, were commissioned.
- A high-throughput experimentation facility for efficient and rapid preparation, screening, and analysis of light absorbers and catalysts was developed.
- New X-ray measurement techniques were developed, in partnership with LBNL and SLAC, for synthesis and characterization of solar fuels materials.
- A catalyst-benchmarking laboratory was established to serve as a resource to define standard testing conditions for solar fuels catalyst performance.
- JCAP has filed 36 invention disclosures and filed 26 patent applications.
- 200+ archival scientific papers have been published, 60% of which are in high impact factor scientific journals.
- JCAP researchers have made over 200 keynote or invited presentations at scientific conferences and technical meetings.

Over the 2010-2015 period, the project plan for JCAP has been focused largely on hydrogen production. At the same time, the solar-fuels revolution is only partially complete, since creation of an integrated generator of carbon-based fuels from carbon dioxide reduction remains a grand challenge. Basic science advances are needed to understand CO₂ reduction catalysis and enable highly selective formation of fuel products. Beyond catalyst discovery, a critical need is the integration of required knowledge, materials and components to form a solar-fuels generator.

In its renewal phase, which will begin on September 30th, 2015, JCAP will capitalize on its developments in water splitting and turn its primary focus to solar-driven carbon dioxide reduction processes under mild conditions. We will pursue routes with high selectivity and efficiency exceeding that of natural photosynthesis. JCAP's renewal is focused on generation of hydrocarbon or alcohol fuel products whose heating value equals or exceeds that of methanol. This requires accelerated discovery of new catalytic mechanisms and materials and development of robust components suitable for integration into a solar-fuels generator.

The goals of the 5-year renewal project include the following advances in catalytic mechanisms, materials discovery and testbed development:

- Discovery and understanding of highly selective catalytic mechanisms for carbon dioxide reduction and oxygen evolution under mild conditions of temperature and pressure, and with input partial pressures of carbon dioxide in air between ambient atmospheric levels of 400 ppm and 1 atm. These advances will inform the design of overall solar-energy-to-fuels components for key processes including light capture, energy transfer, electron transport and charge separation.
- Discovery of electrocatalytic and photoelectrocatalytic materials and useful light-absorber photoelectrodes. This is required to design and construct components for test-bed prototypes that demonstrate selective, efficient CO₂ reduction into hydrocarbon fuels at full solar flux.
- Demonstration, in JCAP test-bed prototypes, of artificial photosynthetic carbon dioxide reduction components and oxygen evolution components that exceed natural photosynthesis in efficiency and rival it in selectivity. Results of these demonstrations will be used to determine the practicality of prototype solar-fuels systems.

How does the integrated research model employed at the hubs advance research goals within the Office of Science and applied energy programs at DOE?

JCAP is funded through DOE's Office of Science, Basic Energy Sciences, Chemical Sciences Division, a basic energy program, and it is headquartered at the California Institute of Technology, with major partners at Lawrence Berkeley National Laboratory and the Stanford Linear Accelerator Laboratory, in addition to partnerships with the University of California campuses at Irvine and San Diego. By design, the hub is integrated across the spectrum of basic and applied research as necessary to achieve its goals, and has the ability to draw on resources from the Office of Science and its partner institutions. The basic science research advances made by JCAP under its Office of Science project are stimulating new technology directions of interest to the DOE applied energy programs in the Office Energy Efficiency and Renewable Energy.

Our strategy recognizes the need to accelerate discovery in the context of a high-risk, high-reward research and development program, and to go beyond discovery to evaluate solar-fuels generator components. The Hub partners have been selected to address these challenges as an integrated, cohesive team. Because of the high-risk nature of a discovery-oriented program, JCAP management and key scientific leaders act as an empowered, flexible team to rapidly assess progress, failure and success, and to dynamically reallocate resources in response to promising developments. JCAP's project plan supports a balance of accelerated discovery and integration in a framework for project evaluation against technical milestones.

A cross-disciplinary and cross-site R&D effort can only thrive in an environment that fosters seamless communication between scientists and with management, across all institutional

partners. From the beginning of JCAP, we configured operations and programs to enable frequent and unhindered communication by: 1) co-locating researchers in JCAP's major laboratory facilities; 2) supporting extensive telepresence/video networking between the sites; 3) incentivizing cross-site visits and cross-site integration teams; 4) organizing regular community-building activities (e.g., weekly research meetings, annual all-hands meetings, seminars, summer schools and short courses.)

The Hub's management structure and communication mechanisms ensure that all members are actively engaged and familiar with JCAP's goals, project plan, timelines and technical progress. Daily, weekly and biweekly meetings are used to present and discuss progress and steps needed to achieve the Hub's research mission. All of the Hub's members review progress against JCAP's Project Plan frequently, using it to set research priorities. JCAP fosters a culture of openness and transparency. For example, research meetings are open to all members of JCAP, and all of the Hub's members use them to provide feedback and to improve their understanding of each other's work. External reviews and self-assessments are disseminated to all members of JCAP so that the status of work and areas for improvement are known and discussed. These regular processes have established strong connections across the Hub that have in turn enabled rapid response times and good teamwork.

There are many examples of JCAP's effectiveness in research integration, one of them culminating in discovery and characterization of a new family of robust metal oxide catalysts for water oxidation. This success was realized in late Spring of 2013 as a result of suggestions to the High Throughput Experimentation project from the Heterogeneous Catalysis project that an investigation of films composed of four elements could yield improved catalysts. The required inks were formulated, the combinatorial plates were made and screened, and compositions from promising regions were scaled up for benchmarking to compare activity quantitatively relative to known catalysts. The compositions were then scaled up yet again for testing in a prototype testbed, synthesized by electrodeposition, and tested. All of these activities occurred over the period of less than twelve weeks. This highly collaborative effort yielded unprecedentedly rapid advances that could only be produced because of JCAP's capabilities and integrated Hub model featuring cross-project teamwork involving researchers at Caltech and Lawrence Berkeley National Laboratory.

To improve and solidify cross-Project integration and collaboration, JCAP added a crosscutting team structure to the Hub in 2013. The teams are complementary to the existing eight projects and serve as a means of directly facilitating cross-project strategy and planning for and execution of, ongoing broad multi-project research. A typical team has members from several projects across JCAP and is led by two early-career staff scientists. Each team is by design a dynamic body, with a set of core members and researchers, who transition in and out of the team depending on the status and type of work being done.

To achieve its aggressive 5-year goals, JCAP leverages the resources and capabilities of other major solar-fuels research programs, of the DOE User Facilities, and of its core industry partners. Working together with key Energy Frontier Research Centers including the Northwestern/Argonne ANSER Center and the UNC Center for Solar Fuels, as well as the Stanford GCEP program, the NSF CCI Solar program, and the Resnick Institute at Caltech, JCAP is actively promoting a robust interactive solar-fuels community in the United States. JCAP will also draw upon state-of-the-art tools of DOE User Facilities including those of the Advanced Light Source at LBNL and Stanford Synchrotron Radiation Laboratory at SLAC for *in situ* and *operando* characterization of catalysis, NERSC (LBNL) for computational theory,

modeling, and simulations, and the Molecular Foundry (LBNL) for material synthesis and nanofabrication. JCAP is developing an industrial partnership, and has had interactions with Dow Chemical, Panasonic, Siemens, and Arkema, all of which have existing research programs and long-term

How does the private sector interact with JCAP? In what way does JCAP prioritize technology transfer of technologies developed at the hub?

There is currently no existing solar fuels industry sector, which is due in part to the basic science challenges that need to be addressed before a solar fuels industry can develop. In fact, this is why a Hub-scale effort is critically needed -to accelerate progress more rapidly in this area- than would be possible via other Department of Energy programs.

JCAP's relationship with the private sector is defined by its goal of building --from basic scientific understanding-- the technology components, intellectual property instruments and institutional relationships to foster a robust future solar fuels industry in the United States. Effective communication and potential collaborations between JCAP and industry could result in foundational discoveries (scientific and technical) that can accelerate the development of a solar fuels industry as well as benefit other industrial processes, for instance those reliant on carbon dioxide reduction.

To facilitate technology transfer, JCAP has been very proactive in filing invention disclosures and patent applications. To date, JCAP has filed 36 invention disclosures and filed 26 patent applications.

JCAP has developed an industrial partnership program to coordinate industrial interactions, and is building collaborations with major multinational industry partners, including Dow, Panasonic, Siemens, and Arkema, all of which have existing research programs in CO₂ catalysis, and long-term strategic interest in the development of a solar-fuel technology. JCAP has also received valuable guidance on strategic direction from its Strategic Advisory Board, which includes industry representatives from Dow Chemical, Boeing, Applied Materials, and Proton Onsite Inc.