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Nanotechnology to improve conversion of solar energy to fuel

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Abstract:

Conversion of solar energy into chemical fuels, no matter the system, requires the coupling of photondriven, single-electron transfer events with fuel-forming, multi-electron catalytic processes. As these processes occur on very disparate temporal scales, their coupling is a significant challenge. Nevertheless, the photosynthetic apparatus, which is essentially composed of a series of Nanoscale molecular machines, provides clear proof-of-concept that such coupling can be achieved. Natural photosynthesis produces "biological fuel" in the form of sugars and other reduced carbon-containing compounds (e.g., lipids, starches and proteins) that are derived from atmospheric carbon dioxide. The plants themselves may be used as primary fuel if directly combusted or secondary fuels (such as ethanol or butanol) may be generated from biomass fermented in reactors. Due to a number of factors, these routes to fuel formation are inefficient. Artificial photosynthetic systems that are inspired by the naturalsystem's Nanocomponents are attractive alternate options. Production of useful chemical fuels directly from sunlight with significantly higher efficiencies than the natural system is possible because such artificial systems need not devote captured energy to the maintenance of life processes. Artificial photosynthetic systems, however, remain in the laboratory stage where increased scientific effort is needed to understand structure-function relationships of components, as well as to develop basic principles for component assembly and integration.

Introduction:

NNI Signature Initiative: Nanotechnology for Solar Energy Collection and Conversion

A. Leverage natural photosynthesis for sustainable production of solar fuels

Enhanced understanding regarding the Nanoscale architecture of the photosynthetic apparatus, along with enzymes and cofactors involved in carbon dioxide reduction and hydrogen formation, will impact both natural and artificial solar fuel production schemes. Specific goals are to

(1) Increase our knowledge pertaining to the complex protein structures and catalytic mechanisms that control and optimize energy flow in natural photosynthesis, as well as mechanisms for component repair and assembly;

(2) Combine Nanotechnology and biotechnology to engineer plants that more efficiently convert solar energy into biomass;

(3) elucidate the Nanoarchitecture of the plant cell wall to understand how it can be modified for enhanced energy storage and/or materials usage;

(4) Engineer photosynthetic microorganisms to cost effectively produce simple fuels such as dihydrogen or more advanced carbon-containing biofuels;

(5) Fully understand the active site chemistry and influence of surrounding proteinaceous Nanostructure on catalytic function of multielectron transfer enzymes and enzymes involved in proton-coupled electron transfer reactions.

B. Develop highly efficient artificial photosynthetic systems

The overarching goal is to construct man-made components (from organic or inorganic molecules, or inorganic semiconductor Nanoparticles) that, as an assembly, convert solar energy into chemical fuels. Efficient solar fuel generation requires three coordinated events—photon absorption, charge separation, and use of the separated charges in fuel-forming reactions. Since the field of photovoltaics is also concerned with light absorption and charge separation, some specific goals to achieve solar fuels are similar to those outlined in Thrust 1. Additional specific goals for this thrust include to

(1) Develop new electrodes or electrode combinations using Nanotechnology to enable a robust, efficient system for direct solar-induced water splitting;

(2) Generate new Nanoscale structures and catalysts derived from earth – abundant materials for photocatalytic water oxidation and photo catalytic carbon dioxide reduction;

(3) Develop innovative architectures for integration of component machinery to produce a functional, efficient photo-electrochemical reactor;

(4) Increase fundamental understanding regarding electronic and molecular interactions that would allow for self-assembly of a Nanoscale solar fuel system.

Expected Outcomes:

New technology that will allow for solar-driven advanced biofuel and bio-based chemical production strategies, robust sunlight-driven reactors that convert water and carbon dioxide into a high-energy-density fuel and related bio-based chemicals

Agency Roles and Contributions

The challenges of realizing a sustainable solar energy economy are significant; the goals can only be met through transformational science and technology that will be achieved by a concerted, interagency effort that addresses challenges spanning multiple diverse disciplines including materials science,chemistry,biology,engineering, and advanced measurement and characterization science. The Department of Energy financially supports an extensive portfolio of research projects that incorporate Nanoscale materials and devices for solar energy collection and conversion. This research is accomplished at DOE labs, universities, and private industry throughout the country. As the nation's leading supporter of energy-related research and development, DOE is in the unique position to be at the hub of this diverse effort. The National Renewable Energy Laboratory along with the five DOE Nanoscale Science Research Centers, provide state-of-the-art fabrication and characterization capabilities for the development of Nanoscale materials and structures. The DOE synchrotron light sources, neutron scattering facilities, and electron microscopy centers provide exceptional characterization at short length and time scales. Integration of scientific advances into commercial scale processes is enabled through a technology pipeline that includes Research, Development, Demonstration, and Deployment.Production of PV modules in China has stimulated competition and reduced prices. In the United States, however, the installed price of Chinese and non- Chinese modules was roughly the same for any given module efficiency .In the first half of 2014, Chinese Tier 1 module players were selling at USD 0.59-0.60/W in China, and USD 0.67-0.79/W in other countries (Bnef, 2014). German modules were selling at EUR 0.69 (USD 0.95)/W. The learning experience for complete PV systems is usually considered slower than that for modules and other hardware parts (inverters, support structures, cables, etc) – a phenomenon with both national and global dimensions. However, in emerging markets, non-module costs often sh as installers gain experience — and also as project density increases, saving significant travel times for sales and marketing staff, and skilled workers.Although module prices seem to have stabilized in 2013, system costs have continued to decline, with cost reductions in California, for example, ranging from 10% to 15%. In Japan, costs of residential PV systems fell from USD 5.9/W in 2012 to USD 4.64/W in 2013 – a 21% reduction.

The quality of PV products has generally increased over the last few years, with reduced variance in PR (Nowak, 2014), but as competition has intensified, some manufacturers have been able to sell lower-quality modules at very low costs. Most common defects were broken interconnections, solder bonds and diodes, or encapsulant discoloration or delimitation. Standards established by International Electricity Commission (IEC 61215 for c- Si, IEA 61646 for TF, IEC 62108 for CPV modules) have proven useful in reducing early failure.There are no widely recognised standards, norms or labels that would tell customers about the behaviour, performance and longevity of various PV products in specific environments. Furthermore, depending on the robustness of the quality assurance system, certification of a module type may only provide insurance with respect to one module out of millions.Grid codes have created other issues. When more energy is fed in to the power grid than is removed from it, the grid frequency increases. Excessively high frequencies render the grid unstable. Until 2011, inverters for PV systems were equipped with an automatic switch-off function triggered at a fixed frequency of 50.2 Hz.As the number of PV systems in Germany increased, however, this requirement meant to protect the grid could have paradoxically put its stability at risk as PV systems switched off abruptly. Power inverters must be able to reduce output when frequency rises too high or to turn themselves off smoothly. In March 2012, Italy required that PV systems over 50 kW and connected to the medium-voltage grid carry out retrofits by the end of March 2013 to solve a problem of under- frequency threshold for disconnection.This resulted in the saturation of the market for interface protection of medium voltage, leading to a suspension of incentives for plants that did not met the deadline.Obtaining permits and, more specifically, getting access to the grid has remained an obstacle for PV in many countries, because PV is not allowed at various voltage levels.

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