Photosynthetic Systems

Portfolio Description

This activity supports fundamental research on the biological conversion of solar energy to chemically stored forms of energy. Topics of study include light harvesting, exciton transfer, charge separation, transfer of reductant to carbon dioxide, and biochemistry of carbon fixation in plants, algae, and photosynthetic microbes. An emphasis is placed on research that intersects biological sciences and energy-relevant chemical sciences and physics, such as in efficient photon capture and charge separation, self-assembly of nanoscale components, predictive design of catalysts, and self-regulating/repairing systems. Capital equipment funding is provided for items such as ultrafast lasers, high-speed detectors, spectrometers, environmentally controlled chambers, high-throughput robotic systems, and computational resources.

Unique Aspects

The Photosynthetic Systems program is the most prominent supporter of basic research in natural photosynthesis in the United States. This distinctive federal program brings together biology, biochemistry, chemistry, and biophysics to uncover the fundamental science of biological capture of sunlight and its conversion to and storage as chemical energy. Through its broad portfolio of projects at universities and DOE national laboratories, the program provides a critical scientific knowledge base that can inspire the roadmap for artificial photosynthesis and enable new approaches for more efficient generation of biomass as a renewal energy source.

Initiated with funding from its predecessor program (Energy Biosciences), the DOE Plant Research Laboratory (PRL) at Michigan State University is a unique facility jointly supported by the Photosynthetic Systems and Physical Biosciences programs. The PRL has been devoted to fundamental plant biology research and the training of graduate students and postdoctoral researchers, the next generation of plant scientists who will provide the knowledge base for meeting future energy needs. Its multidisciplinary research program is focusing on complex questions in photobiology, carbon fixation, and high energy redox reactions and makes use of novel high-throughput, non-invasive phenotyping technologies being developed at the PRL.

Relationship to Other Programs

The Photosynthetic Systems program interfaces with several activities within BES as well as within DOE and other federal agencies.

- Within BES, research efforts are coordinated with the Physical Biosciences program, particularly in areas of carbon fixation and organizational and structural principles of the cellular machinery; the program also interacts with the Solar Photochemistry, Catalysis Science, and Biomolecular Materials programs in bioinspired and biomimetic photosynthetic systems and components.
- This research activity sponsors – jointly with other core research activities and the Energy Frontier Research Centers program as appropriate – program reviews, principal investigators' meetings, and programmatic workshops.
- The basic research supported by the program also collaborates with the genomics- and biotechnology-related programs in the DOE Office of Biological and Environmental Research and the DOE Advanced Research Projects Agency-Energy.

- This activity interacts with the DOE Office of Energy Efficiency and Renewable Energy through its activities in the Solar Energy Technologies program on photovoltaics, the Biomass program on algal and plant feedstocks, and the Fuel Cell Technologies program.
- The program collaborates and coordinates its activities with the National Science Foundation, Department of Agriculture, and National Institutes of Health in areas of mutual interest where there are multiple benefits.

Significant Accomplishments

Through its origin in the Energy Biosciences program, the Photosynthetic Systems program has a rich history of scientific impact. Scientists supported by the program have received numerous awards and prizes including the 2006 Balzan Prize (Plant Molecular Genetics Award) for efforts in developing *Arabidopsis thaliana* as a model plant experiment system. Building on that strong foundation, research in the Photosynthetic Systems program has made significant advances in our fundamental understanding of how nature captures energy from sunlight and converts that energy into chemical energy for the cell.

- Elucidation of the structure of the highly efficient light-harvesting chlorosome antenna complex and characterization of critical components of the algal light-harvesting complex are revealing the structure and molecular components important for light capture.
- Studies of photosynthetic reaction centers have identified regions important for controlling the directionality of charge separation and the efficiency of electron transfer.
- In characterizing the structure/function relationships in photosystem I, scientists are uncovering the fundamental mechanisms of photochemical proton-coupled electron transfer reactions, potentially leading to breakthroughs for coupling photons to fuels in photosynthetic hybrid systems.
- A study of photosystem I components from algae resulted in the development of a biohybrid complex that could produce hydrogen five times more efficiently than observed previously.
- A critical advance has been development of innovative methodologies for collecting simultaneous x-ray diffraction/x-ray emission spectroscopy data from photosystem II using femtosecond pulses from an x-ray free electron laser. Using these cutting-edge techniques, scientists achieved the unprecedented simultaneous imaging of the atomic and electronic structures of photosystem II, gaining critical insights into water oxidation.
- Complementary approaches probing charge transfer mechanisms and pathways in photosystem II are revealing how water molecules are directed to, bound, and activated by the oxygen-evolving complex. Through these studies, a more complete picture is being developed of the energy and electron transfer processes in natural photosynthesis.

Mission Relevance

The impact of research in this activity is to uncover the underlying structure-function relationships and to probe dynamic processes in natural photosynthetic systems. Such fundamental knowledge can guide the development of robust artificial and biohybrid systems for conversion of solar energy into electricity or chemical fuels. Through this understanding, solar fuel systems can be designed which selectively use the best features from nature while bypassing the shortcomings of biology. Achieving this goal would impact DOE's efforts to develop solar energy as an efficient, renewable energy source. Further, the knowledge generated by this research may guide the improvement of photosynthetic efficiency in plants, algae, and microbes which would significantly enhance DOE's efforts to produce advanced biofuels.

Scientific Challenges

Plants, cyanobacteria, and algae use solar energy to convert water and carbon dioxide into chemical energy, i.e. energy-rich organic molecules such as carbohydrates, fat, and protein, which can be collectively termed biomass. Nature has had approximately 3 billion years to modify and refine photosynthesis, a time period 10- to 100-fold longer than humans have had to evolve their complicated biochemical machinery. Understanding nature's complex design for converting sunlight into chemical energy remains a grand challenge for increasing solar energy utilization and enhancing carbon fixation. Despite research efforts, a detailed understanding is still lacking of the structure of the oxygen-evolving complex, the mechanism of action of Rubisco, and the energy dissipation of reactive oxygen species. Molecular, biochemical, and biophysical studies of the mechanisms of the photosynthetic apparatus continue to be much needed, particularly pertaining to light harvesting and energy transduction as well as to the maintenance of the biological integrity of these systems including defect tolerance and self-repair. Increased understanding of the temporal and spatial dynamics and regulation of photosynthesis is another critical research need. Photon absorption and harvesting occur on a femtosecond time scale; charge separation and electron transport on a nano- to picosecond time scale; and photocatalysis and carbon-carbon bond formation on a micro- to millisecond time scale – while presenting experimental and technical challenges, appreciation of the kinetics of each of these processes can provide important insight into natural photosynthetic mechanisms and how they might be altered for use in biohybrid and artificial systems for instance. Such fundamental knowledge of natural photosynthesis can play a significant role in the development of renewable, cost-effective, and environmentally-sustainable energy systems and supplies.

Projected Evolution

Advances in genomics technologies such as metabolomics along with increased availability of plant genomic sequences provide opportunities to leverage the strengths of the Photosynthetic Systems program in molecular biology and biochemistry with powerful capabilities in imaging and computation. This will allow an unprecedented biophysical understanding at the nanoscale of photosynthesis and related processes such as carbon fixation. The program will continue to emphasize research to understand the structural and mechanistic features of photosynthetic complexes; determine the mechanisms behind photon capture and charge transfer; characterize and control the weak intermolecular forces governing molecular assembly in photosynthetic systems; understand the biological machinery for cofactor insertion into proteins and protein subunit assemblies; uncover the biochemical mechanisms that can enhance fuel production in photosynthetic systems to build on results from combinatorial, directed evolution, and high-throughput screening methods; and determine the physical and chemical rules that underlie biological mechanisms of repair and photo-protection.