2.3.9 PHOTOCONVERSION

Technology Description

Photoconversion technology encompasses sunlight-driven quantum-conversion processes (other than solid-state photovoltaics) that lead to the direct and potentially highly efficient production of electrical power or fuels, materials, and chemicals from simple renewable substrates such as water, carbon dioxide (CO_2) and nitrogen. This technology has the potential to eliminate the need for fossil fuels by substituting renewable sources and conversion processes that are either carbon neutral (any carbon generated is reused during plant growth) or carbon free (e.g., hydrogen from water). These technologies also can convert CO_2 into liquid and gaseous fuels via processes that are often termed biomimetic, or bio-inspired.

A photoconversion process to produce hydrogen from metabolically engineered algae.

System Concepts

- Photoconversion processes use solar photons directly to drive biological, chemical, or electrochemical reactions to generate electricity, fuels, materials, or chemicals.
- System components include biological organisms or enzymes, semiconductor structures (photoelectrochemical cells, colloids, nanocrystals, certain plastics or polymers, quantum dots or nanoparticles, or superlattices), biomimetic molecules, dye molecules, synthetic catalysts, or combinations of the above.

Representative Technologies

- Elements of this future solar technology include photobiological, photochemical, photoelectrochemical, photocatalytic, and dark catalytic processes for energy production.
- Photoconversion technologies can produce electrical power, hydrogen, biodiesel, organic acids, methane, methanol, and plastics. These technologies also can remove CO_2 from the atmosphere through photoreduction of CO_2 to fuels, materials, and chemicals. Moreover, they can achieve atmospheric nitrogen fixation (independent of natural gas) and convert biomass to fuels, materials, or chemicals.
- Most of these technologies are at early stages of research, but some are at the development level, and some that produce high-value products are commercial.

Technology Status/Applications

- Power production: dye-sensitized, nanocrystalline, titanium dioxide semiconductor solar cells are 8%-11% efficient and are potentially very cheap. In contrast to solid-state PV solar cells, light is absorbed by dye molecules in contact with an electrolyte rather than solid-state semiconductor materials. Novel photoelectrochemical cells with integrated fuel cells and *in situ* storage for 24-h solar power have been demonstrated at 6%-7% efficiency in 4-by-8-foot panels using a system developed by Texas Instruments, and photochargeable batteries that include electrochemical storage have been demonstrated with 24-h power output. Hot-carrier photoconversion technology for increasing solar-conversion efficiencies (with theoretical efficiency limits of 65%-86%, depending on the solar photon concentration) is making progress. The term "hot carrier" refers to the utilization of highly energetic electrons (called hot electrons and created upon absorption of photons with energies larger than the semiconductor bandgap) for useful chemical production or electrical power, rather than converting the excess electron energy to heat by photon emission. In present photoconversion and photovoltaic devices, the hot electrons cool, and their excess energy is lost as heat in a picosecond (1E-12 sec) or less. Semiconductor nanostructures have been found to slow the cooling time of hot electrons by up to two orders of magnitude, thus enhancing the probability for hot electron conversion.

- Fuels production: Photoelectrochemical and photobiological processes that will lead to hydrogen production from water or gasified biomass are at the early stages of research, and important advances have been made recently; biodiesel, methane, and methanol production from water, waste, and CO_2 are at various stages of R&D; and fuels, such as methanol – produced by the direct electrocatalytic or photocatalytic reduction of CO_2 – are at the early fundamental research stage. Electrocatalytic concentration of CO_2 from the atmosphere is being studied as well; it is of interest to people involved in atmospheric control in small spaces (i.e., submarines and the space station) and has potential for removing CO_2 from the atmosphere in the future.
- Materials and chemicals production: Producing materials and chemicals from CO_2 and/or biomass, as well as producing fertilizer from atmospheric nitrogen and renewable hydrogen, will reduce CO_2 emissions compared with the fossil fuels used currently.
- Photobiological production of pigments (e.g., astaxanthin), health foods, nutritional supplements (e.g., omega-3 fatty acids), protein, and fish food is commercial. Production of biopesticides and pharmaceuticals is under development. Production of commodity chemicals such as, but not limited to, glycerol, hydrogen peroxide, and bioemulsifiers is possible. Photocatalytic production of specialty or high-value chemicals has been demonstrated.

Current Research, Development, and Demonstration

RD&D Goals

- In the near-term, research will focus on applications related to electrical power and high-value fuels and chemicals, where commercial potential may be expected during the next 5 to 10 years. If successful, larger-scale applications of photoconversion technologies may follow in the period from 2010 to 2015, with materials and fuels production beginning in the period 2015 to 2020, and commodity chemicals production in the period from 2020 to 2030.

RD&D Challenges

- Develop the fundamental sciences in multidisciplinary areas involving theory, mechanisms, kinetics, biological pathways and molecular genetics, natural photosynthesis, materials (semiconductor particles and structures), catalysts and catalytic cycles, and biomimetic components. Progress in fundamental science is needed to underpin the new photoconversion technologies.
- Maintain critical mass research groups in vital areas long enough for sustained progress to be made.

RD&D Activities

- A significant level of basic research activities in solar photoconversion is currently being performed by the DOE Office of Science; some exploratory R&D is being performed by DOE Office of Energy Efficiency and Renewable Energy/Office of Solar Technologies.
- Some basic research support by the National Science Foundation and the U.S. Department of Agriculture is complementary.

Recent Progress

- Prototype dye-sensitized nanocrystalline semiconductor solar cells have been demonstrated as power sources in small niche markets. Commercial interest is very high because they also can be configured to produce hydrogen.
- Scientific breakthroughs during the past seven years have been made in microbial and enzymatic R&D; natural photosynthesis; semiconductors, nanostructures, quantum dots, and superlattices; CO_2 catalysis; and energy and electron transfer in artificial donor/acceptor molecules.

Commercialization and Deployment Activities
• Astaxanthin, a pigment synthesized from petroleum, is used as a coloring agent in the poultry and salmon industries. Algal production of the pigment just started in Hawaii and is replacing the fossil version for health and environmental reasons. Large-scale algal ponds are producing high-value chemicals on a commercial basis using photobiological processes. As an example, the current astaxanthin market is $180 M/year and is expected to rise to $1 B/year in five years. • European and Japanese companies are beginning to commercialize dye-sensitized, nanocrystalline cell-powered watches. The market is estimated to be 100 million units. **Market Context** • Besides the applications discussed above, many spin-off technologies are possible. These include optoelectronics, biosensors, biocomputers, bioelectronics, and nanoscale devices.