Introduction to Solar Energy Conversion

Solar energy represents the largest energy input into the terrestrial system. Despite its relatively low power density, this resource could potentially satisfy the global energy demand on its own. The challenges that need to be addressed to make solar energy viable and competitive on a large scale include: enhancing the performance of solar energy conversion systems through increased efficiency and use of durable materials; reducing the material, fabrication, and installation costs so that these systems can be deployed at a large scale; and overcoming the intermittent nature of the resource to allow supply to meet demand at all times.

Photovoltaic energy conversion efficiency has increased steadily in the past decade through enhanced photon absorption and charge transport. Moreover, continuous development of novel device concepts, materials, and fabrication processes has contributed to lowering the cost of solar power. Thin-film solar cells are regarded as a promising route for low-cost energy conversion. Inorganic thin films are relatively mature technologies with record efficiencies above 15%. Organic solar cells are at an earlier stage of development with efficiencies currently ranging from ~9% for polymeric heterojunctions to 10% for dye-sensitized cells. Further research in thin-film technologies is required to increase their efficiency up to the thermodynamic limits, to enhance their stability, and to further reduce their fabrication cost.

Solar thermal technologies are appropriate for large-scale energy production and can be combined with thermal energy storage systems, which offers a practical solution to smooth supply intermittency over time periods of several hours.

Photoelectrochemical systems are another option under investigation to circumvent the intermittency issue of solar power. They hold the promise to efficiently harvest solar energy and convert it into chemical fuels with a single, potentially low-cost device. This conversion strategy allows for the carbon-free – or even carbon-negative when CO_2 is used as a feedstock – synthesis of fuels for electricity and/or transportation, and provides a solution to the intermittency problems without requiring the use of ancillary energy storage systems to match supply and demand.

Currently, GCEP has eight ongoing projects in the solar area that fall across the areas of organic and inorganic thin films, (photo-assisted) thermionic systems, high-efficiency thermo-photovoltaic conversion, and photoelectrochemical production of hydrogen.

Professor Zhenan Bao is developing a carbon nanotube (CNT)-based transparent electrode technology for photovoltaic applications. Her research includes the development of an experimental method to selectively separate metallic from semiconducting nanotubes and to control the morphology of the metallic nanotube network to optimize both the film transparency and the sheet conductivity.

Professors Nicholas Melosh and Zhi-Xun Shen are investigating a novel photon-enhanced thermionic concept that combines photon- and thermal-excitation in a semiconductor material to increase the efficiency of thermionic electron emission compared to current systems.

Professors Shanhui Fan and Peter Peumans from Stanford University in collaboration with Professor Paul Braun from University of Illinois at Urbana-Champaign is developing a thermo-photovoltaic (TPV) device capable of achieving solar-to-electric energy conversion efficiencies higher than the Shockley-Queisser limit for single-junction solar cells. The main components of the system consist of photonic crystals designed to absorb electromagnetic energy over the entire solar spectrum and re-emit light at energies close to and above the bandgap of a single junction photovoltaic cell.

Professors Gavin Conibeer and Martin Green of the University of New South Wales, Professor Jean-François Guillemoles of IRDEP, France, Professor Tim Schmidt of the University of Sydney, and Professors Antonio Marti and Antonio Luque of the Instituto de Energía Solar, Spain, are developing a proof-of-concept device of a hot carrier solar cell using abundant and non-toxic nanostructured materials. The project addresses all the main scientific and technological aspects of such a concept, including the reduction of hot carrier thermalization in the main absorber, the development of selective energy contacts, and the integration of all components into a working device.

Professors Alberto Salleo, Yi Cui, and Peter Peumans are investigating a novel low-cost concept for inorganic multijunction solar cells. The proposed concept uses solution-processed absorbers made of colloidal semiconductor nanocrystals and ZnO or Ag nanowire network-based transparent conductors as an alternative to established technologies based on brittle and high-cost transparent metal oxide films. The overall approach offers advantages such as large flexibility in the choice of active materials, easy control of subcell bandgap using quantum-confinement effects, and the practicability of realizing devices with a large number of junctions.

Professors Mike McGehee and Alan Sellinger of Stanford University began a new project in 2010 aimed at investigating advanced electron transport materials for application in organic photovoltaics (OPVs). The objectives of the proposed work are to design, prepare and characterize a family of new advanced electron transport materials from simple, minimal step, high yield, and inexpensive synthetic processes for application in OPVs.

Professor Harry Atwater of the California Institute of Technology, Professor Mark Brongersma of Stanford University, and Professor Alfred Polman of the Foundation for Fundamental Research on Matter (FOM), The Netherlands, are applying plasmonic technologies to enhance the performance of nanocrystalline semiconductor-based thin film photovoltaics. Nanopatterned metallic films are utilized as transparent electrodes and light concentrators to allow the use of poor electron transport materials – such as low-dimensional semiconductor structures – in very thin (10-100nm) layers of photoactive material. This project also explores potential designs of omnidirectional absorbers that can be integrated into the cell as built-in tracking systems to further enhance cell efficiency.

Professor Zhenan Bao and Alan Aspuru-Guzik embarked on a new project in 2010 aimed at a pathway towards breakthrough performance solar cells by rational organic semiconductor material design.