Future Development of Technology in Dye-Sensitized Solar Cells

Michael GRÄTZEL

Perhaps the largest challenge for our global society is to find ways to replace the slowly, but inevitably vanishing fossil fuel supplies by renewable resources. To realize the sustainability of life on Earth, we need rapid technological progress in renewable energy generation and carbon-free energy resources. The sun provides about 120,000 terawatts to the earth's surface which amounts to six thousand times the present rate of the world's energy consumption. However capturing solar energy and converting it to heat, electricity or chemical fuels, such as hydrogen, at low cost and using abundantly available raw materials remains a huge challenge. Photovoltaic cells are expected to make pivotal contributions to identify environmentally friendly solutions to this energy problem. One technology of great promise is that of dye sensitized mesoscopic solar cells which employ three-dimensional (bulk) interpenetrating network junctions for light harvesting and charge carrier transport using structural elements with features in the 2-50 nm size range. Leading a new generation of solar cells, the DSC is the only photovoltaic device that uses dye molecules or semiconductor quantum dots to absorb photons and convert them to electric charges without the need of excitonic transport of electronic excitation. The role of the sensitizer or quantum dot is to absorb light and generate positive and negative electric charges, which are injected in appropriate charge transport materials, *i.e.* an n-type conductor such as TiO_2 for the electrons and a p-type conductor or electrolyte for the positive charges (holes).

Thus the DSC separates the two functions of light harvesting and charge carrier transport, whereas all known inorganic and organic photovoltaic devices perform both operations simultaneously. This imposes stringent demands on the optical and electronic properties of the semiconductor, *i.e.* its band gap and conduction band or valence band position as well as mobility and the recombination time of photo-generated charge carriers. As a result, the choice of suitable materials that are able to act as efficient photovoltaic converters is greatly restricted. The separation of the functions of light absorption and carrier transport on the other hand opens up a many options for the absorber and charge transport materials. The molecular sensitizer or semiconductor quantum dot is placed at the interface between an electron (n) and hole (p) conducting material. The former is typically a wide band semiconductor oxide, such as TiO_2 , ZnO or SnO_2 while the latter is a redox electrolyte or a p-type semiconductor. Upon photo-excitation the sensitizer injects an electron in the conduction band of the oxide and is regenerated by hole injection in the electrolyte or p-type conductor.

Mesoscopic dye-sensitized solar cells have been under development since our initial report in 1985. Such systems can be manufactured at low cost from earth abundant materials and with minimal environment impact. They presently reach power conversion efficiencies above 11 percent in single-junction-type cells and over 15% in tandem cells providing a technically and economically attractive alternative to conventional p-n junction-based photovoltaic devices.

Future research will focus on further improvements of the solar cell performance without sacrificing cell stability. The light harvesting properties of the solar cells in the near infrared region can be enhanced by modifying the dye or by using small-band gap semiconductor quantum dots as sensitizers. Thus, Professor Segawa's group at the University of Tokyo has developed a Ru polypyridyl complex, whose spectral response extends up to 1000 nm. An important recent breakthrough has been the introduction of cobalt complexes replacing iodide based redox electrolytes, which enabled a stunning increase in the open circuit voltage to values over 1 V when used in conjunction with judiciously designed sensitizers. Donor acceptor substituted Zinc porphyrins have recently reached conversion efficiencies exceeding 12% employing Co-bipy complexes as redox electrolyte. Gains in open-circuit photovoltage V_{oc} are also expected from a better control of the interfacial charge recombination dynamics. New solid-state electrolytes are another attractive research target warranting excellent long term stability. Thus a whole realm of new materials (metal oxides, chromophores and hole transporters) as well as ordered oxide mesostructures will be tested allowing to push the conversion efficiencies of dye sensitized solar cells in the 15-20 percent range.

Dye-sensitized solar cells have already attained efficiencies on the laboratory as well as on the module scale which render them competitive to other thin film solar cells. Their low cost and ease of production avoiding expensive high vacuum steps should benefit large-scale applications. Impressive stability both under long-term light soaking and high temperature stress has been reached fostering first industrial applications. Large scale commercial production of dye sensitized solar cells has started in 2009 and major sales orders have been obtained. These systems will promote the acceptance of renewable energy technologies, not least by setting new standards of convenience and economy.

Michael GRÄTZEL
Professor, École Polytechnique
Fédérale de Lausanne (EPFL)