The Millennium Technology Prize Laureate 2010

"For his invention and development of dye-sensitized solar cells, known as "Grätzel cells". The excellent price/performance ratio of these novel devices gives them major potential as significant contributor to the diverse portfolio of future energy technologies. Grätzel cells are likely to have an important role in low-cost, large-scale solutions for renewable energy. Besides photovoltaics, the concepts of Grätzel cells can also be applied in batteries and hydrogen production, all important components of future energy needs."

Professor Michael Grätzel

Professor, Director of the Laboratory of Photonics and Interfaces, Ecole Polytechnique de Lausanne (EPFL), Switzerland

Swiss citizen, born in Dorfchemnitz, Germany in May 1944.

Timeline

1970 First attempts to realize DSC cells
1988 Grätzel's team tests the first dye-sensitized mesoscopic titanium oxide material on solar cells
1991 Grätzel's landmark Nature paper on dye-sensitized solar cells is published
2009 Mass production of DSC cells begins

Developer of dye sensitized solar cells

The 2010 Millennium Prize Laureate Michael Grätzel is the father of third generation dye-sensitized solar cells. Grätzel cells, which promise electricity-generating windows and low-cost solar panels, have just made their debut in consumer products.

One of mankind's greatest challenges is to find ways to replace the diminishing fossil fuel supply. The most obvious energy source is the sun, origin of almost all the energy found on Earth. The surface of the Earth receives solar radiation energy at an average of 81,000 terawatt – exceeding the whole global energy demand by a factor of 5,000. Yet, we are still figuring out a cost-effective way of harnessing it.

Solar cells, converting energy from the sun into electricity, were first used in the 1950s to power orbiting satellites and other spacecraft. Applied to power generation on Earth, the price does matter. Selected silicon based technology was – and still is – expensive, even if the cost of photovoltaics has declined steadily since the first solar cells were manufactured.

Grätzel's innovation, the dye solar cell (DSC), is a third generation photovoltaic technology. The technology often described as 'artificial photosynthesis' is a promising alternative to standard silicon photovoltaics. It is made of low-cost materials and does not need an elaborate apparatus to manufacture. Though DSC cells are still in relatively early stages of development, they show great promise as an inexpensive alternative to costly silicon solar cells and an attractive candidate for a new renewable energy source.

Imitating Mother Nature

Photovoltaic cells are made of semiconductor materials such as silicon. When light strikes the cell, a portion of it is absorbed within the semiconductor material. This means that the energy of the absorbed light is transferred to the semiconductor. The energy knocks electrons loose, allowing them to flow freely. This flow of electrons is a current. By placing conductive plates on the top and bottom of the photovoltaic cell, the current can be drawn off for external use, say, to power a pocket calculator.

In traditional photovoltaic cells silicon acts as both the source of electrons, as well as conductor of the charge carriers. DSC cells separate light harvesting from charge carrier transport, mimicking the principles of solar energy conversion that natural photosynthesis has successfully adopted over the last 3.5 billion years. We can think plant leaves as tiny factories in which sunlight absorbed in the leaf by chlorophyll converts carbon dioxide and water into oxygen and glucose, providing energy for the plant. In DCS cells' 'artificial photosynthesis,' the leaf structure is replaced by a porous titanium oxide nanostructure, and the chlorophyll is replaced by dye molecules.

Dye-sensitized solar cells consist of titanium oxide nanocrystals that are coated with light-absorbing dye molecules and immersed in an electrolyte solution. Only 10 micrometers thick, the mixture is sandwiched between two glass plates or embedded in plastic. Light striking the dye frees electrons and creates "holes" - the sites of positive charge that result when electrons are lost. The semiconducting titanium dioxide particles collect the electrons and transfer them to an external circuit, producing an electric current.

Marketable consumer applications

Of all renewable energy sources, solar power is one of the most easily exploitable. The only constraint is its price. Using dye sensitized solar cells, grid parity - the point at which photovoltaic electricity is equal to or cheaper than grid power - is much closer. Compared with silicon based cells the dye-sensitized solar cells are considerably cheaper to manufacture. DSC-technology relies on materials that are readily available in large quantities and relatively non-toxic. For example, titanium dioxide, used instead of expensive high purity silicon as a semiconductor, is a cheap white pigment used in paints.
Cells can also be engineered into flexible sheets. Michael Grätzel displays a fabric-like sheet of flexible DSC-panel. "This panel is cut with scissors from the production line."
The panel is manufactured in a low-cost, roll-to-roll process and the production equipment is similar to manufacturing lines used by the printing, coating and packaging industries.

In 2009 one of the DSC licence holders, G24 Innovations, announced the first ever commercial shipment of DSC photovoltaic modules. The first consumer product, backpacks coated with the cheap and flexible DSC solar cell, for on-the-go recharging of portable gadgets, hit the shelves in January 2010.

The flexibility and low weight of DSC panels are important for powering portable electronics, but the technology also has other virtues. Compared to conventional silicon based photovoltaic technology, DSC can produce electricity in low light conditions and can be directly incorporated into buildings by replacing conventional glass panels rather than taking up roof or extra land area. The panels can also be made transparent. "Transparent DSC panels that produce electric power for the building could be a very interesting application for glass facades," Grätzel says.

DSCs are the only solar cells that can be made truly transparent their colour depending on the choice of the sensitizer. By selecting dyes that absorb only in the near IR and UV region it is possible to produce even colourless transparent windows.

Dye-sensitized solar cells reach currently 12 percent efficiency under standard reporting conditions on the laboratory scale while the efficiency of larger modules designed for outdoor conditions is currently about 8–9 %. It is well below the 15% standard for polycrystalline silicon designs. "But in real working conditions the difference shrinks. This is due to the decrease in performance of silicon cells with increasing angle of light incidence, and temperature as well as cloudy conditions where the DSC has an advantage over silicon," Grätzel explains.

Silicon cells only allow you to capture power when light is intense. DSC cells capture power in low light or even rainy conditions. That means the cells give a better performance over the whole day, even if they are less efficient under ideal conditions.

Birth of the Grätzel cell

Leaves of plants are tiny factories in which sunlight converts carbon dioxide gas and water into carbohydrates and oxygen in a wide range of sunlight conditions. In spite of the low efficiency, the process has worked for hundreds of millions of years, and forms the primary energy source for all life on earth.

Since the 1970s, efforts were made to create a better solar cell based on this principle. There were early attempts to cover crystals of semiconductor titanium dioxide with a layer of chlorophyll. However, the electrons were reluctant to move through the layer of pigment, so the efficiency of the first solar cells sensitized in this way was about 0.01 %.

During the 1973 oil crisis Grätzel was a young researcher and it was apparent that alternative sources of energy had to be found. "I was always interested in natural photosynthesis. At the time I was educated, the detail on how photosynthesis worked was not well established. It was far from what we know today. I was intrigued by the way plants use the molecules to generate charges and separate those charges."

In the 1980s Grätzel was working at École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland, doing basic research on nanotechnology. They were the first to make nanoparticles from titanium oxide. The properties of the new material were examined in many ways.

"That was a fundamental study, just driven by our curiosity. Nobody had done it before. However these experiments provided important insight in the sensitization process that formed the scientific basis for the subsequent realization of dye sensitized solar cells."

Researchers were also interested in production hydrogen fuel. "Our hydrogen generating device was not very efficient, but it was based on sensitisation of oxide semiconductors," Grätzel recalls.

Meanwhile, the oil price had plummeted to US $5 a barrel. Research on renewable energy was no longer fashionable.

Then in 1988 Grätzel asked his students to build a photoelectrochemical cell, using the same principle as the sensitisation experiments with titanium dioxide nanoparticles.

"I asked my PhD student **Hans Desilvestro** how the experiment had gone. He did not seem to be too enthusiastic initially, adding that he had only measured a few milliamperes current. I knew it was a lot. Other researchers had only measured micro- or nanoamps."

Instead of using a flat titanium dioxide electrode they had worked with a porous film of very high roughness. This method increased the effective surface area available for absorbing the light by 'many times'- and the sunlight was efficiently converted into an electric current. The first Grätzel cell was born. "We got a present from Mother Nature," Grätzel says laughing.

In 1991 Grätzel and Brian O'Regan reported their research in Nature. *It* was a landmark paper presenting an entirely new paradigm in photovoltaic technology

The reported 7 % efficiency of prototype DSC cells was 1000-fold better than the first attempts in 1970s. Its efficiency competed with silicon cells, which had been around for thirty years. No wonder Grätzel had to convince his colleagues again and again his cells were working. "I always travelled with my cell, ready to give my colleagues a show at their lab."

Skilled pianist – and researcher

Grätzel sometimes still gives a Grätzel cell show to high school students. Using simple demonstration kit, students have the opportunity to be involved in cutting-edge, green chemistry research. Blackberries or raspberries are used as a light-harvesting sensitiser molecule. All the chemicals are mixed and put between glass plates. Exposed to light it produces current enough to power a small fan. Students are as happy as Grätzel and his colleagues were 20 years ago.

Grätzel achieved good grades at school in physics and chemistry – and music. "I had to decide whether to be a pianist, but science looked like a safer bet. It was marvellous to understand how nature works."

As a skilful pianist, he sees art very similar to science. "Science is very creative, like art. Nobody can prevent you from doing an experiment which you think is interesting."

Nobody can deny his creativity in the scientific world: Author of over 800 peer-reviewed publications, two books and inventor of more than 50 patents, his work has already had 60,000 citations, ranking him among the 10 most highly cited chemists worldwide.

Since 1981 he has been full Professor of Physical Chemistry at the Ecole Polytechnique de Lausanne, Switzerland.

International research

After the ground-breaking Nature report in 1991 there was an explosion of research activity across the world into Grätzel solar cells. Numerous research groups are busy developing novel synthetic dyes with even better energy conversion efficiencies.

Grätzel has continued his work with his research group Laboratory of Photonics and Interfaces LPI. Current research focuses on optimization of key parameters of cells, such as spectral response, photocurrent, photo-potentials and long-term stability. Research is also booming on solid sate versions of the DSC where the liquid electrolyte is replaced by solid inorganic or organic hole conductor. Recent investigations include also semiconducting quantum dots or extremely thin absorber layers as sensitizers.

Notable improvement of the lifespan of dye-sensitized solar cells has been obtained by judicious chemical design of the sensitizer.

LPI is also developing nanocrystalline iron oxide films used in conjunction with Grätzel cells to split water into hydrogen and oxygen by sunlight. They have also pioneered in the development of new ionic liquids, which are used as "green" electrolytes in solar cells and other electrochemical devices.

However, the DSC can also be prepared on flexible, non-fragile and lightweight substrates such as plastic foils or metal sheets. Numerous laboratories are developing methods familiar to coating and printing industries, enabling high throughput, cost-efficient roll to roll -type production of the cells. Indeed, the potentially low cell price which follows from fast, large scale mass production makes manufacturing of even lower efficiency and lower lifetime DSC devices economically feasible.

“It started from our laboratory, but during the development there have been so many contributions from all over the world. I have to be grateful to all these people: my students, other laboratories and industry, who had believed in this technology. I am extremely happy this has taken off,” Grätzel says modestly.

Business growing fast

The first commercial DSC applications are already generating power for mobile electronics. The first company to mass-produce flexible dye-sensitized solar cells is shipping its products. The next major step toward inexpensive and large-scale commercialisation of dye-sensitized solar cells might be taken in the building industry. Building-integrated photovoltaics (BIPV) is one of the fastest growing segments of the photovoltaic industry. Photovoltaic materials may be used to replace conventional building materials in parts of the building envelope such as the roof, skylights, or facades.

Glass manufacturer Pilkington North America and DSC material supplier Dyesol recently signed an agreement to form a joint venture to produce electricity generating DSC glass panels for BIPV applications. Dyesol is also developing DSC films integrated onto coil steel for large scale commercial building claddings.

Photovoltaic is the world’s fastest-growing energy technology. Today, solar power accounts for only 0.54% of global energy usage. Of this, the predominant part is solar heat and only 0.04 % solar electricity. The average annual market growth of the photovoltaic industry has been 35–40 % for several years, and, for example, in 2007, grid-connected PV was the fastest growing source of energy with its 83% increase.

In the early 1990s, when Grätzel travelled with his prototype cells, ready to showcase the technology, he already had commercial production in mind. "I was convinced that this finding could be taken to commercial applications. It just took longer than I thought. But that is entirely normal. You have to find the people who believe in your technology, have the money to invest and have the possessions to go over all the hurdles that arise."

LINKS AND FURTHER READING

Publications

"A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO_2 films", Brian O'Regan, Michael Grätzel, Nature 353, Oct. 24, 1991. pp. 737-740.

Links

Wikipedia article about DSC-technology http://en.wikipedia.org/wiki/Dye-sensitized_solar_cell
Photovoltaic technology developments and solar news http://www.pv-tech.org/

Companies:

Dyesol http://www.dyesol.com/
G24 Innovations http://www.g24i.com/
Solaronix http://www.solaronix.com/

Curriculum Vitae of Professor Michael Grätzel

Education
Habilitation and *venia legendi* in Physical Chemistry, Free University of Berlin (1976)
Ph.D. in Physical Chemistry, 1971 (*summa cum laude*), Technical University of Berlin
Diploma degree in Chemistry, 1968 (*summa cum laude*), Free University of Berlin

Positions held
Full Professor, Director of the Laboratory of Photonics and Interfaces, Faculty of Basic Science, Ecole Polytechnique de Lausanne (EPFL) 1981-present.
Head, Chemistry Department, 1991-1993, 1983-1985.
Director of the Institute of Physical Chemistry, 1998-2000, 1980- 1982,
Associated Professor of Physical Chemistry ,EPFL 1977-1981.
Senior Staff Scientist, Hahn-Meitner Institute Berlin, 1974 -1976.
Lecturer, Photochemistry and Physical Chemistry, Free University of Berlin, 1975-1976.
PRF Post Doctoral Fellow, University of Notre Dame, Indiana, USA, 1972 -1974.
Research Associate, Hahn Meitner Institute Berlin, Germany, 1969-1972.

Awards and Academic Distinctions
2009 *Balzan Prize* , Milano Zurich.
2009 *Honorary Professor* , Huazhong University of Science and Technology, Wuhan China
2009 *Honorary Professor,* Institute of Applied Chemistry, Chinese Academy of Science Changchun, China
2009 *Dr.Honoris Causa* , Hasselt University Belgium.
2009 *Galvani Medal* of the Italian Chemical Society.
2008 *Harvey Prize in Science and Technology* , The Technion Haifa, Israel
2007 *First International Prize*, Japan Society of Coordination Chemistry
2007 *Dr. Honoris Causa* Delft University of Technology, The Netherlands
2007 *Kroll endowed Chair*, University of Cornell, Itaca,USA, offered.
2006 *World Technology Award in Materials*. San Francisco, USA.
2005 *Gerischer Prize* of the Electrochemical Society
2005 *Winner, Scientific American Top 50*, ranked amongst 50 leading scientists worldwide
2004 *Laurea honoris causa,* University of Turin (600 Anniversary award).
2003 *ENI-Italgas Price in Science and Environment*
2002 *IBC International Award in Supramolecular Chemistry and Technology*
2002 and 1998 *Venture 2002 McKinsey Award*, Zurich, Switzerland
2001 *Havinga Lecture, Award and Medal*, Leiden, The Netherlands
2001 *Faraday Medal* of the Royal Society of Chemistry, United Kingdom
2000 *Grand European Price of Innovation*
1998 *Eurel Price* of the European Society of Electrical Engineers
1997 *Calveras Award in Photovoltaics*, Denver USA
1996 *Dr.honoris causa*, Faculty of Science, University of Uppsala, Sweden.
1985 *R.A. Plane endowed Chair,* Clarkson University, Potsdam USA, offered.
1984 *Japanese Society for the Promotion of Science Fellow,* Tokyo, Japan
1981 *Chair of Physical Chemistry,* Free University, Berlin offered
1966 *Fellow, Studienstiftung des Deutschen Volkes* (top first percentile of all students).

Honorary Named Lectureships
2010 *The CNR Rao Award Lecture*, Indian Institute of Sciene Bangelore India.
2010 The *Michael Faraday Lecture*, J.Nehru Center for Advanced Scientific Research, Bangalore, India
2009 *The Patrick S. Ncholson Memorial Lecture*, Lake Louise Canada
2009 *John C. Bailar Lectures and Medal* , University of Illinois ,Urbana ,USA
2008 *The 18th Brdicka Lecture,* Karl's University Prague
2008 *The AD Little lectures*, MIT Boston, USA.
2008 *"Lecture at the Leading Edge",* University of Toronto, Canada
2008 *The Earl L. Muettert ies Memorial Lecturer* ,University of California at Berkeley,
2007 *The William Lloyd Evans Lectures and Award* Ohio State University.
2007 *The 6th Distinguished Gouq-Jen Su lecturer*, University of Rochester.
2006 *Rohm&Haas Speaker,* hosted by Stanford University Graduate Students
2006 *The Arthur Birch Lecturer,* Australian National University, Canberra
2006 *The Cady Lecturer,* University of Washington, Seattle, USA
2006 *The Johnson Lecturer,* Cornell University, Ithaca,NY, USA
2004 *Weissberger Williams Distinguished Scientist Lecturer*, Kodak Rochester USA,
2003 *The Dupont Centennial Lecturer*, Dupont Wilmington, Delaware, USA.
1999 *The Weissberger Williams Distinguished Scientist Lecturer*, Kodak Rochester USA
1995 *The Debye Lecturer*, Utrecht, The Netherlands.
1993 *Chemistry Society Inaugural Lecturer* , Dublin, Ireland 1982
1982 *Honorary Lecturer,* University of Texas, Austin Texas.
1981 *GOP Invited Lecturer*, Des Plaines, Illinois, USA

Invited Professorships and Guest Scientist Appointments
2007/2008 Mary Upson Visiting Professor, University of Cornell Ithaca N.Y. USA
2006-2009 Distinguished Invited Professor National University of Singapore.
2003-2006 Honorary part time Chemistry Chair, Delft University of Technology,
2003, Fellow, Hanse Scientific College, Bremen, Germany
1998, 1997, 1995, 1986 and 1981 invited Guest Scientist, NREL, Golden, Colorado USA
1993, Invited Professor, Ecole Nationale Supérieure de Cachan (Paris), France
1988, Invited Professor, University of California at Berkeley, USA.

Professional Assignments, Editorial Boards, Professional Society Memberships
Scientific and Academic Advisory Committee, Weizmann Institute of Science, Israel (2006) *UK Engineering and Physical Sciences Research Council (EPRC) Review College (2003-). Evaluation Board of the NIMC Institute*, Tsukuba, Japan (1999-2006). *Invited panelist*, US Department of Energy Council on Chemical Science, 2005 and 1997. *Expert witness* for the Royal Court of Justice London (2002-2004).
Scientific Committee of the French CNRS, expert for evaluating the Physical Chemistry Laboratory of the University of Paris (URA 75) and the Institute of Electrochemistry of the University of Grenoble, France.
Evaluation Board of Photovoltaic Research, Helmholtz Foundation, Gerrmany 1998.
Evaluation Board, Volkswagenstiftung, Germany (1997-2003).
Editorial Board memberships (past and present):
Chem.Phys.Chem.(Wiley-VCh), Journal of Molecular Catalysis (Elsevier), Langmuir (American Chemical Society), Chemistry of Materials (American Chemical Society), Handbook of Nanostructured Materials and Nanotechnology (Academic Press), Advances in Photochemistry and Photophysics (CRC), Solar Energy Materials and Solar Cells (Elsevier), Renewable &Sustainable

Energy Reviews (Elsevier), Advanced Functional Materials (Springer), Nanostructured Materials (Elsevier), Progress in Photovoltaic Science and Technology. Chemical Physics Letters. Angewandte Chemie (starting 2010). *Topical Editor*, New Journal of Chemistry (Paris, France), special issue on Fractals in Chemistry, 1989, (together with Prof. J. Weber, Geneva)

Professional Society Memberships

Member of the Swiss Chemical Society and the European Academy of Science. Fellow of the Royal Society of Chemistry (FRSC), Honorary member of the Société Vaudoise de Sciences Naturelles.

Publications

include over 800 research papers in peer-reviewed scientific journals and 60 reviews or invited book chapters and editor, author or co-author of three books. His publications have received over 60'000 citations (h-index 115) ranking him amongst the most highly cited scientists in the world.

Patents (over 50 total of which 12 are selected below)

1988 "Photoelectrochemische Zelle, Vefahren zum Herstellen einer derartigen Zelle, sowie Verwendung der Zelle". Swiss Patent Nr. 505/88.

1990 " Photovoltaic Cells," GB patent 9008512.7, United States patent (US) Nr. 5,350,644, Japanese patent (JP)Nr. 2101079.

1992 "Cellule Photovoltaïque dont la jonction active a une surface développée supérieure à sa surface projetée" European patent (EP) Nr 0606453. Chinese patent (CN) Nr 34640.Japanese patent (JP) Nr 3391454. United States patent (US) Nr 5482570.

1992 "A Process for making photo-electrochemical cell and a cell made according to said process". German patent (DE) Nr P 42 07 659.5, European Patent (EP) Nr 0584307. US Nr. 5,525,440 . Australian patent (AU) Nr 675779. South Korean patent (KR) Nr 0301267, Japanese patent (JP) Nr 3681748.

1993 "Pile photoélectrochimique et électrolyte pour cette pile, Swiss patent CH Nr 3889/93. United States patent (US) Nr 5,728,487, Australian patent (AU) Nr 687485, European patent (EP) Nr 0737358.

1995 "Primary and secondary electrochemical generator having a nanoparticulate electrode". United States patent (US) Nr. 5'569'561.

1995 "A battery of photovoltaic cells and process for manufacturing the same ".European patent (EP) Nr 858669. United States patent (US) Nr 6,069,313. Australian patent (AU) Nr 728725. Japanese patent (JP) Nr 4087445.

1997 "Transition metal complex photosensitizers and use of this complex in a photovoltaic cell" United States patent (US) Nr 6,245,988. Australian patent (AU) Nr 743120. European patent (EP) Nr 0983282.

2000 "Solid state heterojunction and solid state sensitized photovoltaic cell". United States patent (US) Nr 6,861,722. Australian patent (AU) Nr 779449. United States patent (US) Nr 7,042,029.

2004 "Photoelectric conversion device". Japanese patent (JP) Nr. 4185490. European patent (EP) Nr. 1507307. Australian patent (AU) Nr. 2003231536. Chinese patent (CN) Nr. ZL 03801649.4.

2005 "Tandem Cell for Water Cleavage by Visible Light. "United States patent (US) Nr. 6,936,143 B1.

2007 "Photocatalytic film for the cleavage of water into hydrogen and oxygen by sunlight". United State patent (US) Nr. 7,271334B2 2007

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