Next-Generation Technologies in the USA

© R. McConnell¶

National Center for Photovoltaics, National Renewable Energy Laboratory
80401–3393 Golden, CO, USA

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This paper describes the highlights of exploratory research into next-generation photovoltaic (PV) technologies funded by the United States Department of Energy (DOE) for the purpose of finding disruptive or leap frog technologies that have a chance of leaping ahead, both in terms of vastly higher conversion efficiencies and greater penetration of the PV energy marketplace. Next-generation PV technologies are defined as those not in production or only in limited production because of the need for additional long-term research, development, innovation, and commercialization. Since 1999, DOE and the National Remewable Energy Laboratory have funded 33 universities and companies to explore these concepts, with a total annual budget of about $2 million US per year.

Next-generation photovoltaic (PV) technologies are defined as those not in production or in limited production of less than 1% of the conventional PV market sales. Exploratory research into these next-generation technologies resulted from the consensus at a 1997 conference often referred to as „The Leap Frog Conference." This conference was convened to review the viability of conventional PV technologies and to present and discuss next-generation PV technologies that might conceivably „leap frog" present-generation solar cells, either in terms of higher efficiency, lower cost, or both [1]. The consensus was that the present generation, typically using crystalline silicon, was exhibiting incremental performance increases and cost decreases, with diminishing hope for a dramatic breakthrough that would lead to a much more commercially viable position in the energy marketplace. The next-generation technologies have been called by various terms — Future Generation, Beyond the Horizon PV, PV for the 21st Century, Third-Generation PV, FULLSPECTRUM, etc. — but all these terms allude to dramatically lower cost, higher efficiency energy service from PV. It is important to note that a new crystalline-silicon-based technology can still be a next-generation technology. But rarely will any next-generation technology be discovered unless many exploratory research projects are intentionally conducted by qualified scientists. This situation has been popularized as an optimistic affirmation credited to the Greek poet and playwright Sophocles, who enjoined us all: „Look and you will find it — what is unsought will go undetected."

In 1998, the National Renewable Energy Laboratory (NREL) issued a request for proposals for next-generation PV concepts and conducted a rigorous competition leading to the selection of 18 university groups solely in the basis of the quality of the research proposed and the capabilities of the researchers. Each proposal, funded for three years, was to conduct exploratory research into a next-generation PV topic. This set of projects — called Future-Generation PV — explored many PV ideas, including nanoparticles in polymers, new III-V materials for higher efficiency concentrator cells, porous silicon cells, nanorod solar cells, new transparent conducting oxides, and several studies of the Staebler–Wronski effect in amorphous silicon. Early results from some of the projects appeared at a second conference, entitled „Photovoltaics for the 21st Century," along with an identification of exploratory research opportunities in conventional, as well as next-generation, photovoltaic technologies [2]. The third conference in 2001, called „Photovoltaics for the 21st Century II," highlighted presentations of the major results from all of the Future Generation projects [3].

A second request for proposals in 2001 — called Beyond the Horizon PV — yielded 15 new three-year projects on technologies such as dye solar cells, liquid-crystal solar cells, multijunction small-molecule cells, polymer cells, nanocrystalline silicon cells, lower cost substrates for III–V concentrator cells, and non-vacuum fabrication processes for polycrystalline thin-film materials. We have published an article containing descriptions of these Beyond the Horizon projects, as well as the earlier Future Generation projects, along with references to published articles from each of the projects [4].

The most recent request for proposals, retaining the earlier title of Future-Generation PV, was completed in 2003 and provided many strong, intriguing proposals for exploratory PV research. However, at the time of writing this manuscript, budget uncertainties have delayed the announcement of any new awards.

The mandate for these exploratory projects has been to investigate every plausible technology for generating electricity from solar cells, with the goal of identifying „leap frog" possibilities. One of these technologies — high-efficiency III–V solar cells for use in solar electric concentrators — appears likely to become a „leap frog" technology, with the distinct possibility of leaping ahead of existing technologies, rather than taking the more characteristic development time of 10 to 20 years (see Fig. 1). Concentrating sunlight is a technology as old as Archimedes, and focusing sunlight onto solar cells has been explored since the 1970s, so it is not a new technology. However, as noted in the preface for the „Leap Frog" conference [1]: „Indeed, many of these presentations referenced a long history for their ideas. What has changed, perhaps, is the

¶ E-mail: robert_mcconnell@nrel.gov

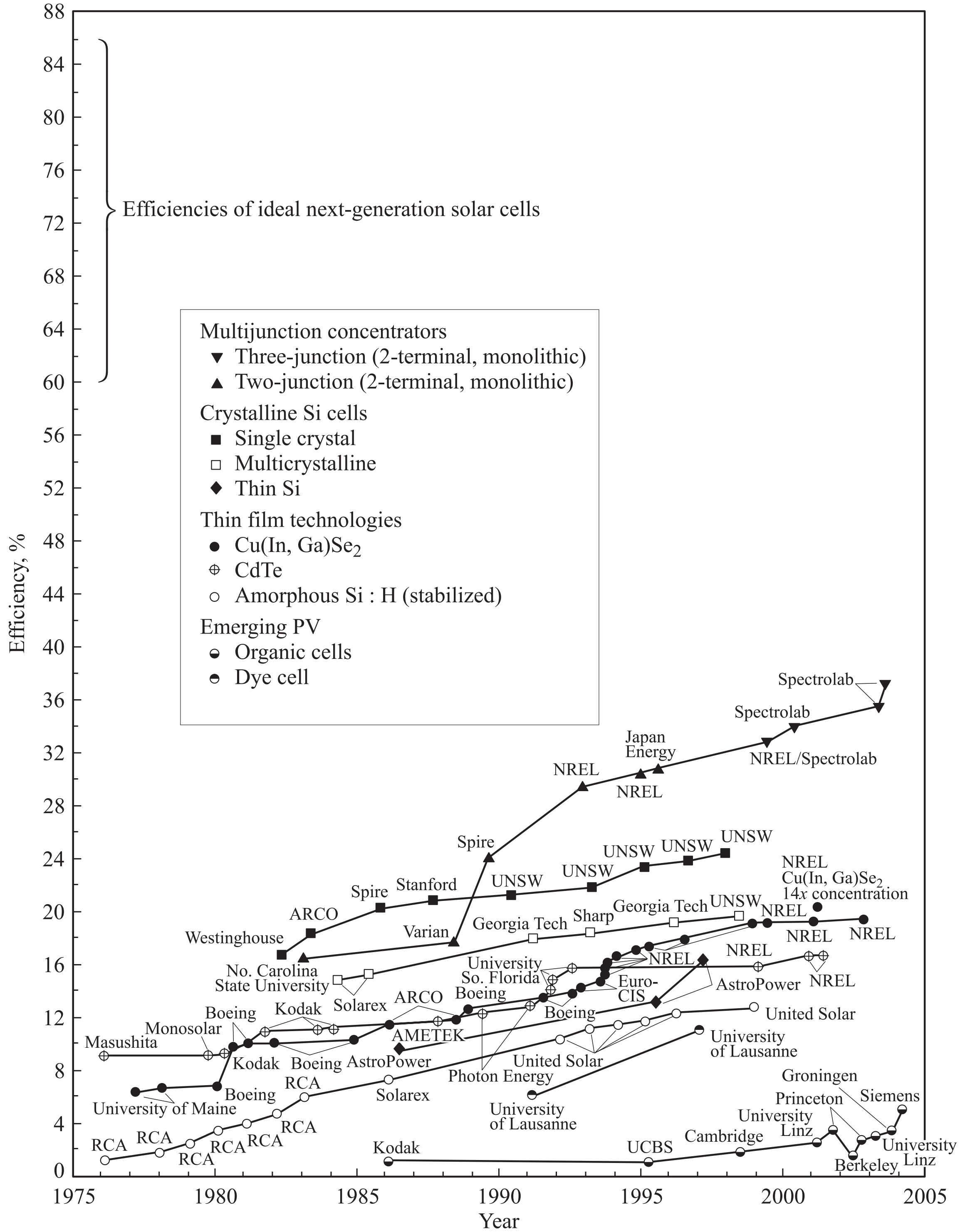

Figure 1. Highest conversion efficiencies of present and next-generation solar cells measured at NREL. Note that we have a long way to go to reach the desired efficiencies in the 60% to 85% range.

availability of new technologies and discoveries that might make some of these concepts realistic.“ In the case of solar electric concentrators, the development of high-efficiency crystalline silicon solar cells (now at about 26% efficiency under concentration) in the 1980s and the subsequent development of high-efficiency III–V solar cells (now at about 37% efficiency) in the 1990s have led to an increased possibility that this technology will become a „leap frog“ PV technology (see Fig. 1). Both the Future Generation and Beyond the Horizon projects included exploratory research into higher efficiency III–V solar cells and low-cost substrates for them. However, in addition to early

Figure 2. To dramatize the impact of the new high-efficiency III–V solar cells on solar concentrator technology, each of these nominal 20-kW dish concentrators developed by Solar Systems Pty Ltd in Australia could be rated at over 30 kW simply by replacing the crystalline silicon solar cells with III–V cells in each receiver of the sun's rays.

funding for in-house research on III–V solar cell at NREL, there was significant early funding from the Department of Energy's Office of Science and later funding provided by other U.S. government agencies (principally the U.S. Air Force within the U.S. Department of Defense) to develop manufacturing facilities for III–V solar cells used for communications satellites. Recently, we have gone further to facilitate the emergence of this technology in the terrestrial energy service market by convening two international solar electric concentrator conferences [5,6], conducting a system analysis [7] of the cost of future solar electric concentrator technologies, and supporting the development of concentrator test standards to increase the probability that solar electric concentrators will operate reliably when they appear in the marketplace [8].

One of the markets that solar electric concentrators are entering is distributed utility grids, especially those powered by diesel generators. Figure 2 is a photograph of a 220-kW solar concentrator power station that is operating in a diesel grid. This application is cost effective because it saves diesel fuel, which is costly to transport to the generators. Incorporating III–V technology into such a solar station is relatively simple; the receivers are replaced with ones containing the new III–V solar cells. In this case, the power of the same solar station shown in Fig. 2 will increase to about 350 kW.

A second possible „leap frog" PV technology is based on organic materials. These materials absorb sunlight and create charge carriers through a different process than that occurring in almost all the inorganic solar cells, whether conventional or next generation. Photon absorption in almost all inorganic solar cell materials leads to the creation of *independent* electrons and holes that move by means of potential gradients within the solar cells. The photon absorption process in organic materials creates excitons — *bound* pairs of electrons and holes — which diffuse to a nearby internal boundary with another material, where they dissociate into separate charge carriers at the boundary [9]. This fundamentally different photovoltaic process leads to much different length scales: the diffusion lengths for excitons are typically 10 nm, so that the required thicknesses of organic solar cells are measured in 10s of nanometers, instead of microns or 100s of microns for crystalline silicon solar cells. Organic solar cells have been demonstrated for a variety of organic materials, including organic dyes, polymers, small molecules, and hybrids of polymers containing inorganic nanoparticles. Inorganic nanoparticles are another breeding ground for exciton creation by photon absorption. The efficiencies of organic solar cells are still quite low, but there is another application having a higher value market than energy service that in spurring research and development. The leveraging of engineering development costs — usually an order of magnitude more expensive than exploratory research efforts — is critical to bringing a new solar technology to market. This scenario has been true with crystalline silicon (the integrated circuit industry), amorphous silicon thin films (thin-film transistors for displays), and III–V solar cells (satellites for defense and commercial applications). Without this leveraging, the time it takes to get to market is measured in decades instead of years. One such organic semiconductor application is the organic light-emitting diode (organic LED), which appears today in high-value display applications such as cellular phones. Equally relevant may be the recent interest of the U.S. Defense Advanced Research Projects Agency in developing portable organic solar cells to replace heavy battery packs for soldiers on reconnaissance missions. These plastic solar cells are expected to weigh considerably less and bend without breaking, and they are showing improving efficiencies. Further, low cost is eventually expected as these organic semiconductors don't use scarce, expensive, or toxic elements and their manufacture involves relatively low process temperatures and, sometimes, no vacuum. Long-term reliability is slowly being demonstrated for organic LEDs, but this is certainly an important issue remaining for organic solar cells.

It is our firm conviction that the probability of finding new technologies is increased when high-quality scientific research is conducted. As an example and a highlight of the early Future Generation contracts, Paul Alivisatos at the University of California, Berkeley, has been a pioneer in exploring nanoparticles in polymer solar cells. His group demonstrated how solar cell efficiency could be improved by changing the geometry of nanoparticles. They improved the efficiency of their solar cells by a factor of two by incorporating long nanorods in place of nanospheres, and they have ideas for the next nanogeometry likely to improve efficiencies further (see Fig. 3). The quality of their scientific achievement in growing different nanostructures was highlighted by the publication of their work in Science [10].

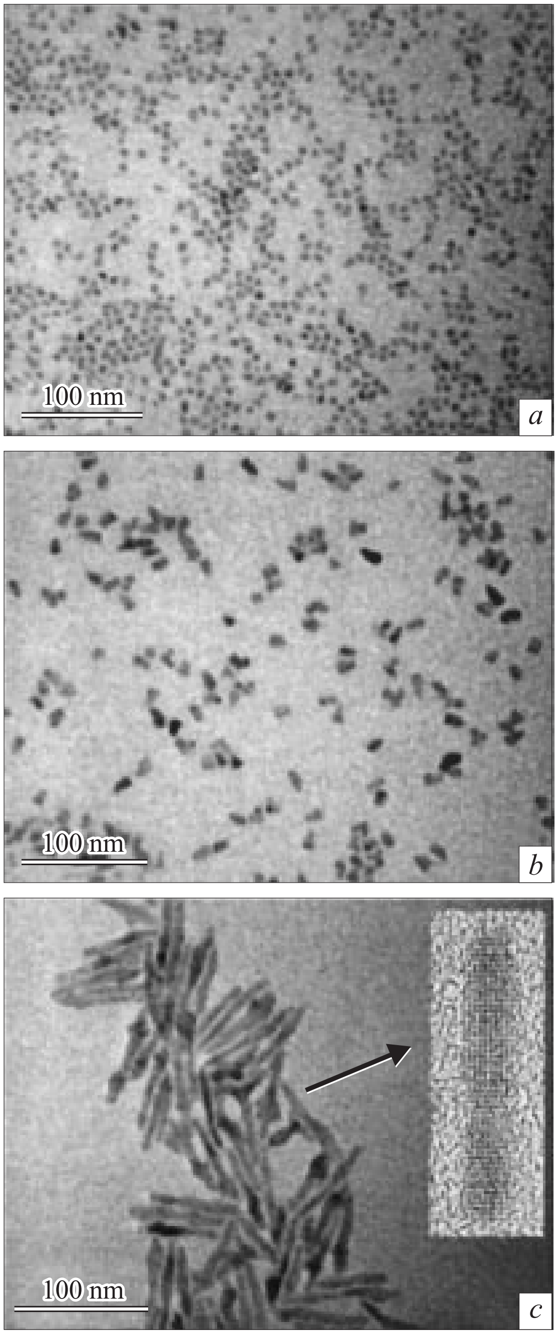

Рис. 3. Innovative growth techniques at University of California Berkeley produced these nanospheres (*a*), short rods (*b*), and long rods (*c*) for incorporation into polymer solar cells having improved efficiencies.

Another example is Steve Forrest at Princeton University, a winner of one of the Beyond the Horizon contracts, who leads the development of another approach to developing organic solar cells. The approach is based on developing an interpenetrating heterojunction between an organic donor and organic materials. Using small molecules instead of polymers, his group discovered the importance of maintaining contact surface morphology during annealing to improve their solar cell efficiency by 50%. Their results recently appeared in Nature [11].

The most recent request for proposals conducted by NREL in 2003 specifically mentioned the Third Generation technologies championed by Martin Green, Hans Queisser, Antonio Luque, Arthur Nozik, and others [12,13]. These technologies typically have high theoretical efficiencies, between 60% and 85%, and involve radically different photovoltaic processes, such as producing two pairs of electrons and holes with one photon (two excitons per photon in the organic analogue) or minimizing phonon creation in hot-carrier solar cells. These technologies are all deserving of continued exploration as the search for next-generation PV technologies continues throughout the world.

It is important to acknowledge that this work has been carried out with the support of the U.S. Department of Energy through its Solar Energy Technologies Program in its Energy Efficiency and Renewable Energy Office. I also wish to acknowledge the contributions of all the principal investigators selected for funding under the Future Generation and Beyond the Horizon PV projects. Finally, it is a pleasure to acknowledge Lawrence Kazmerski, Director of NREL's National Center for Photovoltaics, who has always been a supporter for these efforts, and Richard Matson, a long-time scientist at NREL who became intrigued and later enthusiastic in championing next-generation PV technologies.

References

[1] *Future Generation Photovoltaic Technologies* (ed. by R.D. McConnell AIP Conf. Proc. **404**, Woodbury, N.Y., 1997).
[2] V. Kapur, R.D. McConnell, D. Carlson, G.P. Ceasar, A. Rohatgi, eds. *Photovoltaics for the 21st Century* (ECS Proceedings, Volume 99-11, Pennington, New Jersey, 1999).
[3] R.D. McConnell, V. Kapur, eds. *Photovoltaics for the 21st Century* II (ECS Proc. **2001**–**10**, Pennington, New Jersey, 2001).
[4] R. Matson, R. McConnell. *Conf. Record. 29th IEEE Photovolt. Specialists Conf.* (IEEE: N.Y., 2002) p. 1343.
[5] R.D. McConnell. *First Int. Conf. Solar Electric Concentrators* (NREL/EL-590-32461: Golden, Colorado, 2002).
[6] R.D. McConnell. *Int. Solar Electric Concentrator Conf. for the Generation of Electricity or Hydrogen* (NREL/EL-520-35349: Golden, Colorado, 2004).
[7] R.D. McConnell. In: *Renewable Energy Technology Characterizations* (EPRI TR-109496: Pleasant Hill, California, 1997) p. 4.
[8] R. McConnell. In: *Proc. 16th Eur. Photovolt. Solar Energy Conf.* (James & James, London, 2000) p. 2237.
[9] B.A. Gregg. L. Phys. Chem. B., **107**, 4688 (2003).
[10] W.U. Huynh, J.J. Dittmer, A.P. Alivisatos. Science, **295**, 2425 (2002).
[11] P. Peumans, S. Uchida, S.R. Forrest. Nature, **425**, 158 (2003)
[12] M. Green. *Third Generation Photovoltaics* (Springer, Berlin, 2003).
[13] *Next Generation Photovoltaics* (ed. by A. Marti, A. Luque Institute of Physics, London, 2004).

Редактор Л.В. Беляков