Advances in Photovoltaic Science and Technology for Solar Electricity

J. M. Poate[1], R. T. Collins[1], P. C. Taylor[1], and L. L. Kazmerski[2]

[1]Colorado School of Mines, Golden, Colorado 80401, USA

[2]National Renewable Energy Laboratory, Golden, Colorado 80401, USA

JPoate@Mines.edu

1. Introduction

Future scenarios to meet the world's energy and environmental needs will require a multiplicity of energy sources including, for example, conventional and non-conventional fossil fuels, nuclear fission and a whole spectrum of renewable energy sources. One of the most interesting and important questions is the role that solar energy will play in this scenario. World energy consumption is predicted to grow from the present day requirements of 13 TW/YR to 30TW/YR in 2050. These figures should be contrasted with the roughly 125,000 TW of solar power that strikes the earth at any time. Solar energy can be captured in many ways, in this review we focus on photovoltaic (PV) electricity generation. At present, PV production is almost insignificant compared to fossil fuel based electricity generation. The key issue in moving PV generation forward is cost – PV generated electricity is almost an order of magnitude more expensive than coal based electricity.

The significance and potential of PV generation has clearly been grasped with PV manufacturing growing exponentially at 30%, or greater, per year. This growth has been mainly driven by government subsidies in Japan and Germany. For example, the EU has a goal of generating 22% of electricity by renewable sources in 2010. In the United States, the Solar America Initiative has the goal of making PV power competitive with other forms of renewable energy by 2015. The generation of competitive PV electricity generating will depend on manufacturing expertise, with its concomitant historic learning curve, and scientific breakthroughs [1,2] that will guarantee increased efficiency.

2. Key Features

The birth of the modern era of PV solar cells occurred at Bell Labs in 1954 when Chapin, Fuller and Pearson [3] produced single crystal Si solar cells based on p-n junctions. Wafer-based crystalline Si modules dominate the PV market today. Fig. 1 from Green [4] shows the cost per peak watt ($/Wp) as a series of dashed straight lines in terms of efficiencies and areal costs. Any combination of areal cost and efficiency that is on a given dashed line produces the same cost per peak watt indicated by the line. The area labeled I refers to the first generation of Si based solar cells where the cost per peak watt is $3.50/Wp. For PV to be fully competitive with fossil based fuels the cost must be reduced to $0.40/Wp. The areas labeled II and III present the module costs for generation II (thin-film PV) and generation III (advanced PV structures). These are the areas that demand scientific and manufacturing breakthroughs.

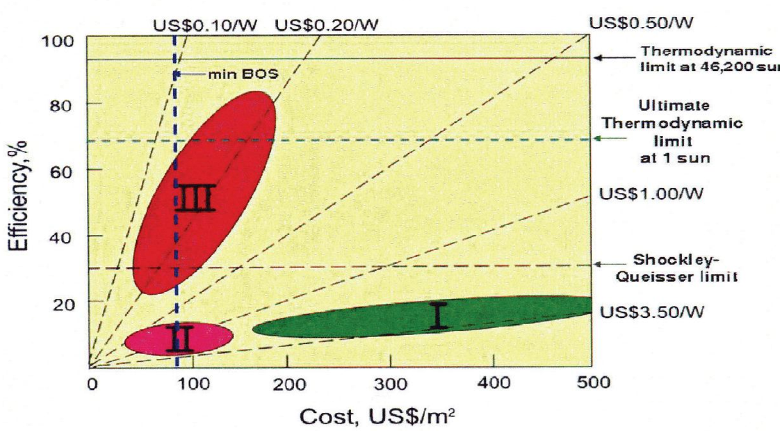

Fig. 1. PV power costs ($/Wp) as a function of module efficiency and areal costs from Green [4].

The learning curve [5] for PV module manufacturing shows a 20% price reduction for every doubling of accumulated sales. Therefore, assuming, 30% per year market growth, the cost will drop by a factor of two every 8-10 years. At this rate, reaching a competitive cost with today's fossil fuel costs will take 30-40 years. For PV technologies to make a real impact on the worlds energy needs, the time interval for competitive costing has to be shortened to 10-15 years. The learning curve, however, derives primarily from wafer based Si (generation I) technologies and there is concern that it may be difficult to maintain let alone accelerate with wafer based silicon technology. The goal of becoming cost competitive will only be achieved by new technologies with dramatically reduced manufacturing and improved efficiencies. Hence the need for generations II and III.

Generation II technologies are those thin-film (< 10 μm) solar panels that are currently being manufactured. The inherent advantage of thin film manufacturing is the promise of drastically reduced manufacturing costs. These technologies [6] include amorphous and nanocrystalline silicon, cadmium telluride (CdTe), copper indium diselenide ($CuInSe_2$), various copper-indium-gallium-sulphur-selenium (CIGS) alloys, and perhaps organic polymers for low-efficiency, niche-market applications. The amorphous and microcrystalline silicon panels are usually manufactured using DC or rf plasma enhanced chemical vapor deposition from silane. These panels either use glass or stainless steel substrates. The stainless steel substrates incorporate a "roll-to-roll" process using a continuous sheet of material. The CdTe panels are usually manufactured by sublimation or some form of vapor phase transport. This segment of the market is growing very rapidly. The $CuInSe_2$ and CIGS panels are usually manufactured by sputtering or perhaps by physical vapor deposition. Most of the chalcogenide-based panels also use glass or steel substrates. In these thin film technologies there is great interest in flexible substrates such as plastics for low-cost applications where efficiency is not the primary goal. In these thin-film technologies the efficiencies in commercially available panels are less than about 10 %. In the past, there have been issues with degradation and premature failure of packaging in all of these technologies, but modules in current production appear to have overcome these problems.

Generation III technologies emphasize scientific and technological innovation and attempt to create non-incremental "jumps" in the cost efficiency performance of solar electricity production. They are sometimes defined as approaches which do not rely on conventional p-n junctions. Organic and dye sensitized solar cells are examples. A more formal definition involves cells capable of higher efficiency then the single junction Shockley-Queisser [7] conversion efficiency limit of roughly 30%. Multijunction cells and quantum dot approaches fall into this category. In general, all of the above are classified as third generation technologies.

In dye sensitized cells, the dye coating on a nanostructured oxide electrode serves to harvest solar energy. Carrier injection into the oxide and an electrochemical redox reaction are involved in collection and transport of charges created in the dye. Conversion efficiencies near 12% have been achieved in laboratory scale devices. Small molecule and large molecule (e.g. polymer) organic semiconductors are also under active development for solar energy conversion. The large exciton binding energy and extremely short exciton diffusion lengths in these molecules, however, demand different device architectures from traditional p-n junction solar cells. Nanoscale organic-organic and organic-inorganic composites to create bulk heterojunctions are under active investigation. Polymer-fullerene bulk heterojunctions have demonstrated laboratory efficiencies near 5%. For both the above classes of cells the potential for extremely low cost structure derived from solution synthesis and plastic processing is a major driver. Other potential advantages include compatibility with flexible substrates and with novel printing-based patterning.

Tandem or multijunction approaches integrate multiple absorbers with different band gaps into the same cell. A broader portion of the solar spectrum is absorbed while minimizing thermal relaxation losses. Tandem solar cells based on III-V compound semiconductors have the highest reported efficiencies, near 40%, and are used extensively in space power applications. For terrestrial PV applications, coupling cells, which are relatively expensive, with solar concentration systems may reduce ultimate systems costs to a level competitive with other second generation technologies. Tandem approaches are also being developed using lower cost materials systems such as amorphous silicon/crystalline silicon tandem cells [8]. Double junction and triple junction tandem cells of amorphous silicon/ amorphous silicon-germanium alloys have been on the market for some time. Quantum dot-based solar conversion harnesses nanoscale phenomena to, once again, allow a larger fraction of the solar spectrum to be utilized. Approaches based on multiple exciton generation (two or three excitons generated per incident photon) minimize the losses associated with thermalization of carriers created by above band gap absorption. Intermediate band solar cells use dots to create states in the semiconductor bandgap that allow sub-band gap photons to be captured without sacrificing the output voltage of the device. The fundamental effects involved in device operation have been demonstrated for quantum dot solar cells, but integration into high efficiency working devices has not yet occurred. This makes these higher risk, but also potentially very high reward, approaches.

3. Conclusions

The Sun offers a virtually inexhaustible source of energy. A prime candidate for tapping this source is PV technology but two goals must be achieved for the technology to make a major impact; manufacturing costs must be reduced and conversion efficiencies must be increased. PV technologies that are being investigated to realize these goals cover a remarkable range of physical structures and materials. The ability of researchers to rise to these challenges will have a profound effect on our energy supply and environment.

4. References

1. U.S. Department of Energy, Office of Science, 2005, "Basic Research Needs for Solar Energy Utilization: Report on the Basic Energy Sciences Workshop on Solar Utilization," April 18-21.
2. Kazmerski, L.L., 2006, "Solar Photovoltaics R&D at the Tipping Point: A 2005 Technology Overview," J. Electron, Spectroscopy vol. 150, no. 105.
3. Chapin, P., Fuller, C., and Pearson, G., 1954, "A New Silicon p-n Junction Photocell for Converting Solar Radiation into Electrical Power," J. Appl. Phys, vol. 25, no. 676.
4. Green, M.A., 2004, "Third Generation Photovoltaics: Advanced Solar Energy Conversion," Springer-Verlag: Berlin, Germany.
5. Surek, T., 2005, "Crystal Growth and Materials Research in Photovoltaics," J. Crystal Growth, vol. 275, no. 292.
6. Feldman, S.D., Ohno, T., Kaydanov, V., and Collins, R.T., 2004, "Luminescence Studies of the effects of Cu Doping Cds/CdTe Solar Cells," Appl. Phys. Lett., vol. 85, no. 1529.
7. Shockley, W. and Queisser, H.J., 1961, "Detailed Balance Limit of Efficiency of p-u Junction Solar Cells," J. Appl. Phys, vol. 32, no. 510.
8. Craig Taylor, P., 2006, "Mott Lecture – The Localization of Electrons in Amorphous Semiconductors: A Twenty – First Century Perspective," J. Non-Cryst. Solids, vol. 352, no. 839.

Speaker's Biography

John Poate is Vice President of Research and Technology Transfer at the Colorado School of Mines. The bulk of Poate's research career has been spent at Bell Labs where he was Head of the Si Processing Research Department. His prior career has also spanned academia, where he was Dean of the College of Science and Liberal Arts at NJIT, and industry where he was Chief Technology Officer and Vice President of Axcelis Technologies. He is past President of the Materials Research Society and Fellow of the American Physical Society. In 2002, he received the John Bardeen Award of the Metallurgical Society.