Evolution of Perovskite Photovoltaics and Decrease in Energy Payback Time

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A major thrust for endorsing nanostructure-based solar cells (e.g., quantum dot solar cells (QDSCs) or dye-sensitized solar cells (DSSCs)) as next-generation photovoltaics is the simplicity of designing thin-film photovoltaic devices using simple benchtop procedures under ambient conditions. Significant strides have already been made toward understanding the mechanism of operation of these solar cells and developing strategies to improve their photoconversion efficiency. The recent emergence of organometal halide perovskites as light energy harvesters has rejuvenated further interest in designing thin-film mesoscopic solid-state solar cells (MSSCs). The design of perovskite photovoltaics, which mainly stems from the developments of DSSCs and QDSCs, has increased the enthusiasm among the scientists working in the field. The mechanistic details of charge separation and charge transport within a organometal halide perovskite film coated on a mesoscopic oxide film differ from those of a thin-film semiconductor PV. Snaith's and Grätzel's groups, however, recently reported construction of perovskite solar cells with efficiencies greater than 15%, thus positioning perovskite solar cells in the same photovoltaic club as that of thin film PV technology employing CdTe or CIGS semiconductors (DOIs: 10.1038/nature12509 and 10.1038/nature12340).

In a Perspective published in an earlier issue, Prof. Nam-Gyu Park discussed the emergence of organometal halide ($CH_3NH_3PbX_3$ (X = Cl, Br, or I)) perovskite solar cells (Park, N.-G. *J. Phys. Chem. Lett.* **2013**, *4*, 2423−2429). The ability of these pervoskite thin films coated on a mesoscopic oxide film to deliver significantly higher photovoltage than semiconductor quantum dots and possibly minimizing reflection losses lays the foundation for achieving efficiencies greater than 20% in the future. Such a potential squarely gives a competitive edge for developing into commercially feasible devices. The editorial of Prof. Juan Bisquert, *The Swift Surge of Perovskite Photovoltaics*, which accompanied this Perspective, highlighted the merits of perovskite PV (Bisquert, J. *J. Phys. Chem. Lett.* **2013**, *4*, 2597−2598).

Prof. Henry Snaith (in this issue) jogs down the trail of developments that led to the breakthroughs in organometal halide perovskite solar cells (Snaith, H. J. *J. Phys. Chem. Lett.* **2013**, *4*, 3623−3630). The evolution of the pervoskite cell, as illustrated in his Perspective, is shown in Figure 1. In order to differentiate the mechanism of photocurrent generation in these perovskite films from that of sensitized photocurrent generation in DSSCs and QDSCs, Snaith coined the term meso-superstructured solar cell (MSSC). His demonstration of the use of Al_2O_3 instead of TiO_2 as the mesoscopic support in solar cells with high photoconversion efficiency indicated that the photocurrent mechanism differs from that of sensitization mechanism. Because the mesoporous alumina scaffold acts as a superstructure, its role is to increase the effectiveness of the photoactive perovskite layer. The debate on the mechanism of photocurrent generation is likely to continue. Having relatively high absorptivity and an ambipolar nature of transporting charge carriers in the opposite directions, organometal halide perovskites enable the design of relatively thin layer cells. Two possible scenarios for future developments are projected in this Perspective. The first one is to exclude alumina and create a porous perovskite films infiltrated with a transparent charge transporter, and the other one is to create a p−i−n heterojunction with uniform thin-film processing. Given the potential of developing low-cost, high-efficiency solar cells, the future of pervoskite solar cells or MSSCs as viable PV alternatives seems quite strong.

While renewable energy (e.g., photovoltaics) allows us to develop clean energy conversion processes, the implementation of the technology also demands energy input from other resources as an initial investment. In future years, the electricity produced by the installed photovoltaic panels will offset the energy consumed during the initial installation and operation process. While considering PV or any other renewable energy technologies, it is important to consider the availability of resources, energy input for production, installation, and recyclability after completion of the active lifecycle and the energy payback time. It is interesting to note that as late as in 2008, global PV technology consumed 75% more energy than it produced and has only recently become a net energy producer.

Recently, Dale and Benson employed a model to forecast electrical energy requirements to scale up the PV installation and determine the net energy balance of global photovoltaics (Dale, M.; Benson, S. M. *Environ. Sci. Technol.* **2013**, *47*, 3482−3489). It should be noted that the energy consumption in designing, installing, operating, and decommissioning solar panels is a major factor in determining the cumulative energy demand (CED) of a photovoltaic system. This factor, which is also being associated with Green House Gases (GHG), determines the energy payback time for a given photovoltaic system. According to Dale and Benson, the increasing photovoltaic installation around the globe (nearly 40% growth rate during the years 2000−2010) has lengthened the time required for net energy gain. The estimated "pay back time" reflects the energy consumed over the whole life cycle of the solar cell. According to this model, if the current growth continues at the same rate, PV will be a net energy provider globally by the year 2020.

The demand for economically viable high-efficiency solar cells has been the major driving force for exploring next-generation solar cells. Another factor that is an integral part of designing the photovoltaic devices is the cumulative electricity demand (CE_eD) measured in terms of $kW\,h_e/W_p$, where $kW\,h_e$ is the electrical energy equivalent of the energy consumed in the PV production and W_p the electrical power output after installation. The distribution of CE_eD compiled for various PV technologies is shown in Figure 2 (taken from Dale and Benson's work). It is interesting to note from this analysis that
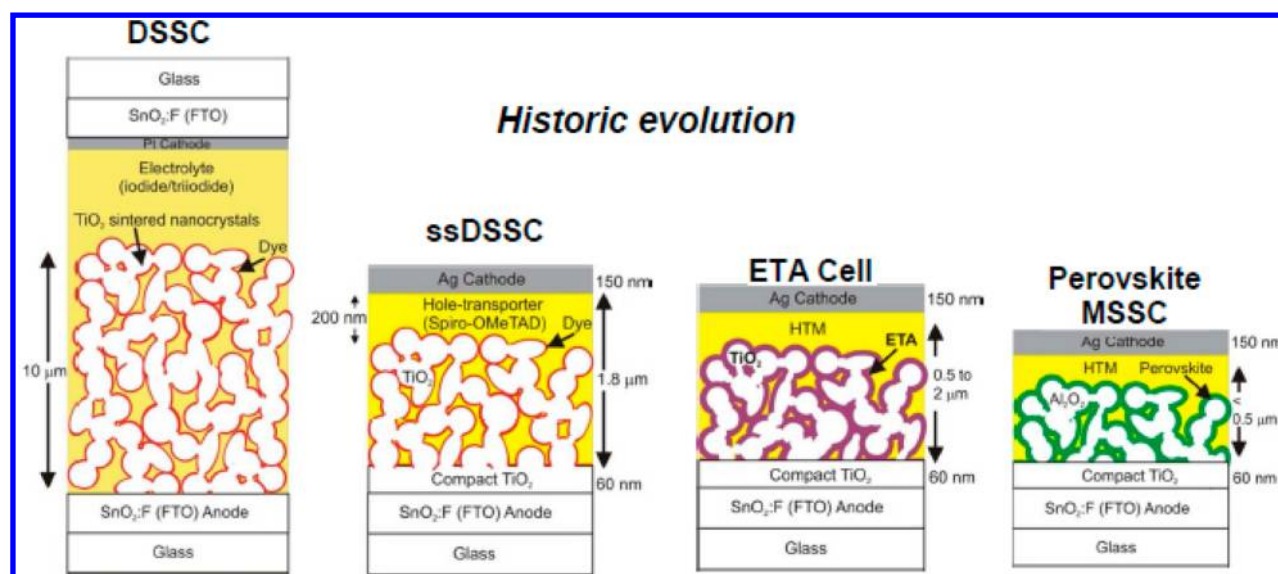
Figure 1. Historic evolution of the solution-processed solar technology, starting from the electrolyte-based mesoscopic DSSC, the solid-state DSSC (ssDSSC), the extremely thin absorber (ETA) cell, to the MSSC. Reprinted from Snaith, H. J. *J. Phys. Chem. Lett.*, **2013**, *4*, 3623−3630.
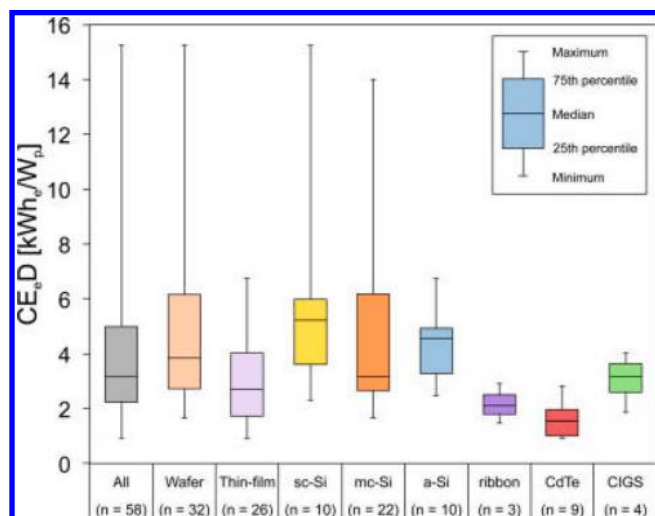
Figure 2. Distribution of estimates of CEeD $[kW\,h_e/W_p]$ of PV systems for a variety of technologies (sc-Si, mc-Si, a-Si, ribbon, CdTe, and CIGS). In general, thin-film technologies have a lower CE_eD than wafer technologies. CdTe has the lowest CE_eD of all of the technologies. (Reprinted from Dale, M.; Benson, S. M. *Environ. Sci. Technol.* **2013**, *47*, 3482−3489.)

■ AUTHOR INFORMATION

Notes

Views expressed in this Editorial are those of the author and not necessarily the views of the ACS.

■ RELATED READINGS

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(3) Snaith, H. J. Perovskites: The Emergence of a New Era for Low-Cost, High-Efficiency Solar Cells. *J. Phys. Chem. Lett.* **2013**, *4*, 3623−3630.

(4) Park, N.-G. Organometal Perovskite Light Absorbers Toward a 20% Efficiency Low-Cost Solid-State Mesoscopic Solar Cell. *J. Phys. Chem. Lett.* **2013**, *4*, 2423−2429.

(5) Bisquert, J. The Swift Surge of Perovskite Photovoltaics. *J. Phys. Chem. Lett.* **2013**, *4*, 2597−2598.

(6) Dale, M.; Benson, S. M. Energy Balance of the Global Photovoltaic (PV) Industry — Is the PV Industry a Net Electricity Producer? *Environ. Sci. Technol.* **2013**, *47*, 3482−3489.

the CE_eD is significantly lower (ranging between 1 and 7) for CdTe and other thin-film PV than that for the silicon-wafer-based PVs (ranging between 2 and 16). Because a smaller CE_eD reflects shorter energy payback time, we see significant advantage of thin-film technologies in reducing GHG. Although cost estimates for perovskite PV have yet to be established, one can foresee the thin-film PV trend that it might follow. Furthermore, given the simplicity of its fabrication and relatively high power conversion efficiencies, we can expect perovskite photovoltaics to offer more advantages than thin-film PV.

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