Tengfei Zhang[1], Huicong Chang[1], Yingpeng Wu[1], Peishuang Xiao[1], Ningbo Yi[1], Yanhong Lu[1], Yanfeng Ma[1], Yi Huang[1], Kai Zhao[1], Yongsheng Chen[1]*, Xiao-Qing Yan[2], Zhi-Bo Liu[2] and Jian-Guo Tian[2]
[1]Key Laboratory of Functional Polymer Materials and Center for Nanoscale Science and Technology, Collaborative Innovation Center of Chemical Science and Engineering, Institute of Polymer Chemistry, College of Chemistry, Nankai University, Tianjin 300071, China. [2]Key Laboratory of Weak Light Nonlinear Photonics, Ministry of Education, Teda Applied Physics School and School of Physics, Nankai University, Tianjin 300457, China.
*e-mail: yschen99@nankai.edu.cn

---

# Solar research not finished

**To the Editor** — Since photovoltaic (PV) cells were first seriously proposed as a large-scale source of terrestrial electric power in 1973[1], PV module prices have dropped from ~US\$500 per watt of electricity generated to <US\$1 per watt in 2015 (1973 monetary values converted to 2015 US dollar equivalent).

At the same time, deployment volume has grown spectacularly: 36% of all added US electric power generation capacity in 2014 came from PV. Global PV shipments were projected[2] to top 50 GW in 2015, representing a ~US\$100 billion per year industry, propelling PV to a status as the largest optoelectronics industry sector in the world, bigger than flat-panel displays or solid-state lighting. Based on typical 25-year warranties, this deployment rate, even if it didn't grow, would result in more than 1 TW generation capacity in the field by 2040.

While this spectacular success should be celebrated, many PV researchers have recently been dismayed to see shrinking public PV research and development (R&D) funding (both in the US and in other countries). At the same time, private sector investment in start-up solar companies has plummeted since many venture investors lost money during the last cycle of PV panel oversupply, which resulted in decreases in panel prices and profit margins[3]. Many perspectives can be heard: those working on integrating renewable energy into the grid may suggest that PV materials research is effectively 'done' and the key remaining challenge is improved grid integration. In contrast, PV researchers note that the solar conversion efficiency of commercial PV modules is still less than half of the theoretical limit. Some argue that, since silicon PV has already been commercialized, further public investment in PV R&D should focus on alternatives such as thin films, while others argue that silicon has already shown itself to be the 'winner', and further PV R&D should focus primarily on advanced silicon concepts. To funders looking to reduce expenditure, a tempting translation of this 'fund me, don't fund them' debate is simply to hear only the 'don't fund them' part and conclude that the timing is right to reduce PV R&D funding. While tempting, this would be premature. There are substantial gains to be had through further R&D investment in PV module efficiency, reliability, and cost reduction, which are needed and are vital for the full success of the sector.

Is PV really cheap enough? Today, PV system prices are low enough to successfully compete with conventional power sources without subsidies in sunny locations with high electricity prices, and close to competitive in many more. The ability of PV to compete depends on many things. When peak electricity demand and the supply of solar electricity align, new PV power avoids the need to expand conventional power plants, meaning that the PV system saves both the cost of the avoided fuel usage and the avoided cost of capital expansion of a conventional power plant[4]. However, as more PV is deployed, the peak demand for non-PV electricity shifts later in the day, and a new PV system allows conventional plants to be turned off during the day, avoiding fuel cost, but no longer avoids the need to install additional conventional power plants to meet the peak demand that may now occur after sundown[5].

PV reaching 'grid parity' (meaning that the projected cost of electricity for a PV project is comparable to local grid electricity prices) denotes a useful milestone, but this is just the first step. For higher penetration of the market, PV systems must cost even less to cover the additional costs of storage or transmission so that solar generation can be dispatched to cost-effectively meet electricity demand more broadly in both time and space.

All parts of the PV industry have reduced costs and must continue to do so. First Solar has demonstrated that thin-film modules can be lower in cost than silicon modules, inspiring continued exploration of a wide range of PV concepts. However, while the opportunity for additional research investment is vast, the world of PV R&D has changed with the realization that silicon PV can hit low prices. There was a time when alternatives were explored with the expectation that silicon PV prices could not be decreased below US\$2 W$^{-1}$. Then, when silicon module prices dropped below US\$2 W$^{-1}$ and manufacturers laid out a roadmap for hitting US\$1 W$^{-1}$, competitors were skeptical. Now silicon modules are selling below US\$1 W$^{-1}$ and US\$0.50 W$^{-1}$ prices are anticipated. This reality of silicon module prices below US\$1 W$^{-1}$ has fundamentally changed PV R&D. A proposal for a new innovative approach to PV that is projected to hit US\$1 W$^{-1}$ is no longer of practical interest (though it might be of scientific interest). And while researchers must now work harder to identify solar absorber materials and device concepts that can surpass what has already been demonstrated, they may find it easier to identify research directions that can change the world by addressing the dispatchability challenge, demonstrating the natural evolution of research agendas as a technology matures. Solar electricity will truly change the world when its night-time 'price at the outlet' is lower than that of today's electricity.

Forty years ago PV research focused on increasing efficiency and reducing solar cell or module cost. Today our perspective has broadened to the PV system level, and even the grid level, and so research objectives must look to reduce the combined cost of both generating and dispatching the electricity. Thus, we need PV R&D to not only continue to address the old themes of PV cost, efficiency and reliability, but also to address all aspects of grid reliability ranging from the practicalities of flowing electricity in two directions to keeping the lights on at night when the Sun isn't shining. As we explore new frontiers that build on the impressive momentum of the PV industry and address the R&D challenges for future PV technology and the means to dispatch it, solar energy will be capable of supplying electricity not only at a scale that significantly reduces pollution and mitigates climate change, but also at a price low enough to bring economic prosperity to the entire world.

References

1. *Photovoltaic Conversion of Solar Energy for Terrestrial Applications Workshop* (23–25 October 1973).
2. Intersolar: global PV growth to top 50 GW in 2015, report says. *PV Magazine* (11 June 2015); http://go.nature.com/sRClzb
3. Zheng, C. & Kammen, D. M. *Energy Policy* **67,** 159–169 (2014).
4. Mills, A. & Wiser, R. *Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot Case Study of California* (2012); http://emp.lbl.gov/sites/all/files/lbnl-5445e.pdf
5. Mai, T. *et al. Renewable Electricity Futures Study Volume 1: Exploration of High-Penetration Renewable Electricity Futures No. NREL/TP-6A20-52409-1* (National Renewable Energy Laboratory, 2012); http://www.nrel.gov/docs/fy12osti/52409-1.pdf

Acknowledgements

The views expressed in this article are those of the authors alone and do not represent the position of the National Renewable Energy Laboratory or other organizations.

Competing financial interests

All of the authors are engaged in research related to solar energy. Thus, the authors have a financial interest in this piece, but an equivalent financial interest is held by any researcher writing an opinion editorial related to their field. We acknowledge the conflict and have been mindful of its effect in writing this document.

Sarah Kurtz[1]*, Harry Atwater[2], Angus Rockett[3], Tonio Buonassisi[4], Christiana Honsberg[5] and John Benner[6]

[1]National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, Colorado 80401, USA. [2]Director of the Joint Center for Artificial Photosynthesis at the California Institute of Technology, Pasadena, California 91125, USA. [3]Department of Materials Science and Engineering, University of Illinois, 1304 W. Green Street, Urbana, Illinois 61801, USA. [4]Director of the Photovoltaics Research Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA. [5]Director of the Quantum Energy and Sustainable Solar Energies Research Center, 551 E Tyler Mall, Tempe, Arizona 85287, USA. [6]Executive Director of the Bay Area Photovoltaic Consortium, 476 Lomita Mall, McCullough Building 135, Stanford, California 94305, USA.

*e-mail: sarah.kurtz@nrel.gov

---

# On nanostructured silicon success

**To the Editor** — Recent Letters by Piggott *et al.*[1] and Shen *et al.*[2] claim the smallest ever dielectric wavelength and polarization splitters. The associated News & Views article by Aydin[3] states that these works "are the first experimental demonstration of on-chip, silicon photonic components based on complex all-dielectric nanophotonic structures." Here, we question the rationale behind the competition for a small device footprint as set out by the authors of the two papers[1,2] and also point out a lack of appropriate historical context in the three contributions[1–3].

The definition of footprint for nanophotonic devices is often ambiguous. Very small devices can be obtained by sacrificing device performance such as transmission or bandwidth. Hence, before venturing on a race for the smallest devices, one should accurately define a set of rules, for example, a minimum transmission efficiency over a certain wavelength interval when considering splitters. As an example, Guan *et al.*[4] have previously theoretically proposed a polarization beamsplitter with a footprint of $1.8 \times 2.5\ \mu\text{m}^2$, which is smaller than the $2.4 \times 2.4\ \mu\text{m}^2$ footprint experimentally demonstrated by Shen *et al.*, although with lower efficiency due to plasmonic losses. So which design is better?

Regarding appropriate historical context, despite inclusion of some citations in ref. 1, we believe that refs 1–3 do not give the full impression that inverse design and experimental demonstrations of complex, all-dielectric nanophotonic structures have been pursued by our group and others for more than a decade. Our first work in 2004[5] demonstrated a complex 2D design for a photonic crystal Z-bend and since then we have presented systematic designs of devices with increasing complexity[6], including wavelength and mode division multiplexers, mode converters[7] and fully 3D designs based on time-domain simulations[8]. Specifically, in 2007 we experimentally demonstrated a wavelength splitter similar to the device of Piggott *et al.* using a similar footprint in a photonic crystal[9]. Also, our work[10] (cited by Piggott *et al.*) considered the design of a drop filter, which is a more difficult problem than the wavelength splitter. Thus, the concluding statement in the Letter by Piggott *et al.* "This device provides functionality that has never before been demonstrated in such a small structure" is inaccurate.

Shen *et al.* report robustness against fabrication tolerances in the form of thickness variations and Piggott *et al.* report indirect robustness against manufacturing tolerances through a multi-frequency strategy. However, device thicknesses are usually well defined before fabrication, whereas in-plane geometric variations introduced during fabrication are much more pronounced due to for example misalignment, diffraction and proximity effects. In previous work we have included such effects directly in the inverse design procedure and hence ensured robustness against spatial errors and the elimination of the need for inverse lithography procedures[11,12].

Piggott *et al.* report computing times of 36 hours on a GPU machine and Shen *et al.* use 140 hours on a parallel CPU machine for their examples with 400 design variables. Based on these reports, Aydin expects a drastically increased computation time when allowing the permittivity profile to vary in the third dimension as well. In fact, using the so-called adjoint method for sensitivity analysis (previously reviewed by us[6]) and systematic mathematical programming techniques, the computing time becomes almost independent of the number of design variables and depends largely on the computing time for the physical system, for example, the forward finite-difference time-domain or finite-element simulations. Hence, our fully 3D wavelength-splitter design[8] did not take longer to compute than its 2D geometry-restrained counterpart.

In their final remarks, the authors of refs 1–3 speculate on the future uses of the design methodologies presented, such as in plasmonics, metasurfaces and metamaterials, as well as in light trapping. We have already applied the topology optimization concept to a wide range of such applications. A literature search will reveal applications in bandgaps, slow light, plasmonics, photovoltaics, cloaking, structural colours, and so on. The topology optimization concept that originated in mechanical engineering and applied mathematics is more than 25 years old[13] and our research group is now approaching discretizations with more than 1 billion design variables for a full-scale airplane wing design. We foresee similar design resolutions being applied to 3D photonic device designs in the not-so-distant future. ❐

References

1. Piggott, A. Y. *et al. Nature Photon.* **9,** 374–377 (2015).
2. Shen, B., Wang, P., Polson, R. & Menon, R. *Nature Photon.* **9,** 378–382 (2015).
3. Aydin, K. *Nature Photon.* **9,** 353–355 (2015).
4. Guan, X., Wu, H., Shi, Y. & Dai, D. *Opt. Lett.* **39,** 259–262 (2014).
5. Borel, P. I. *et al. Opt. Express* **12,** 1996–2001 (2004).
6. Jensen, J. S. & Sigmund, O. *Laser Photon. Rev.* **5,** 308–321 (2011).
7. Frandsen, L. H. *et al. Opt. Express* **22,** 8525–8532 (2014).
8. Elesin, Y., Lazarov, B. S., Jensen, J. S. & Sigmund, O. *Photon. Nanostruct. Fundament. Appl.* **12,** 23–33 (2014).