POLICY FORUM

RENEWABLE ENERGY

Terawatt-scale photovoltaics: Trajectories and challenges

Coordinating technology, policy, and business innovations

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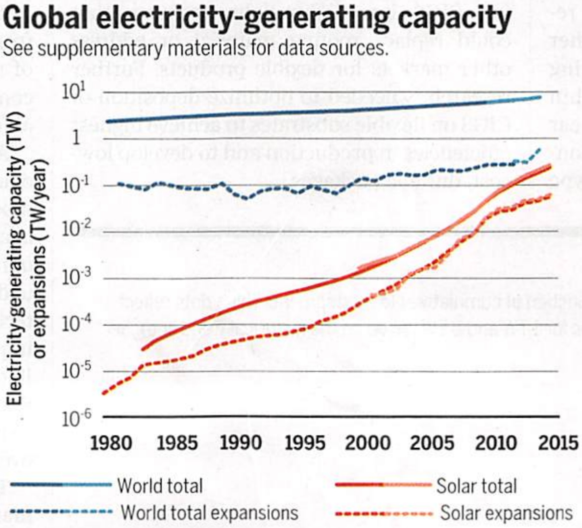
The annual potential of solar energy far exceeds the world's total energy consumption. However, the vision of photovoltaics (PVs) providing a substantial fraction of global electricity generation and total energy demand is far from being realized. What technical, infrastructure, economic, and policy barriers need to be overcome for PVs to grow to the multiple terawatt (TW) scale? We assess realistic future scenarios and make suggestions for a global agenda to move toward PVs at a multi-TW scale.

Total renewable power capacity (not including hydroelectric) grew by a factor of 9.2 from 2000 to 2015, from 85 to 785 gigawatts (GW). Over this same period, solar PV capacity grew by a factor of ~57, from 4 to 227 GW (*1*). The relative growth rate of solar has also been substantially greater than the growth in demand for electricity (see the first graph).

Much progress to date has been enabled by a combination of policy initiatives and technology advances. In Germany, the Renewable Energy Law of 2002 offered a generous feed-in tariff (FIT, payments to energy users for renewable electricity they generate) without a cap on the number of installations. The resulting expansion of the market in Germany encouraged rapid buildup of the PV supply chain. Between 2007 and 2012, the global PV market expanded by an order of magnitude—from ~3 to ~30 GW (*2*). Global manufacturing capacity grew even more rapidly, mostly in China, with portions of the supply chain growing to 60 to 100 GW/year. Estimates point toward continued, but slower, growth in coming years, reaching or exceeding a ~100 GW/year global market in 2020.

Historically, even the most optimistic International Energy Agency (IEA) projections for an energy pathway consistent with limiting the global increase in temperature to 2°C have underrepresented actual deployment of PVs during the past decade (see the second graph). This tendency has been a general characteristic of many PV growth predictions.



Global electricity-generating capacity

See supplementary materials for data sources.

The majority of installations in 2009–2012 were in Europe, but PV markets are expanding in more regions of the globe (see fig. S1.) However, the upfront cost can be high, so incentive programs and regionally tailored project finance structures still drive primary markets.

With the extension of the Investment Tax Credit through the end of 2019, PV installations in the United States are projected to continue at ~10 to 15 GW/year through 2020. California, leading the nation with 13% of electricity from solar in 2016, has taken the unique approach of mandating installation of storage in parallel with future renewable energy capacity.

With generous FITs and streamlined interconnection, permitting, and financing policies, the German PV market grew rapidly beginning in 2008, peaking at more than 7 GW of annual installations in 2010–2012. Annual installations fell dramatically beginning in 2013, as challenges associated with continued support of generous incentive programs began to appear.

Japan has seen accelerated deployment of PVs since the introduction of FITs and associated policies in 2012. With ~11 GW installed in 2015, Japan began to encounter grid constraints in specific utility companies' service areas and a rapid increase in surcharges. The government introduced an additional qualification scheme for PV projects and decided to implement a scheduled reduction of the FIT beginning in fiscal year 2017—measures expected to create a sustainable and stabilized market.

POTENTIAL COST REDUCTIONS

We consider two data-driven approaches to evaluate potential for further PV price reduction: (i) extrapolating the historical experience curve; and (ii) a bottom-up technoeconomic analysis to identify how total life-cycle costs can be reduced.

Major deviations from the historical price versus experience curve for PV modules have been driven by shortages (e.g., polysilicon in the mid-2000s) or oversupply (e.g., in recent years) (see the third graph). Recent analysis suggests that it will be difficult to support manufacturing expansion and innovation at current profit margins (*3, 4*); thus, prices may return to the historical curve in coming years. Extrapolation of the linear curve suggests a \$0.50/W and \$0.25/W module price for cumulative deployment of 1 TW and 8 TW, respectively.

Recent technoeconomic analysis has mapped potential paths to a levelized cost of electricity of \$0.03/kWh that could be achieved in the United States by lowering the module price to \$0.30/W, increasing module efficiency to 25%, decreasing the balance of systems costs (all components other than the PV panels) to \$0.35/W, and improving reliability (*5*). Reaching an average module price of \$0.30/W is consistent with the third figure, once cumulative installations

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GRAPHIC: N. CARY/SCIENCE

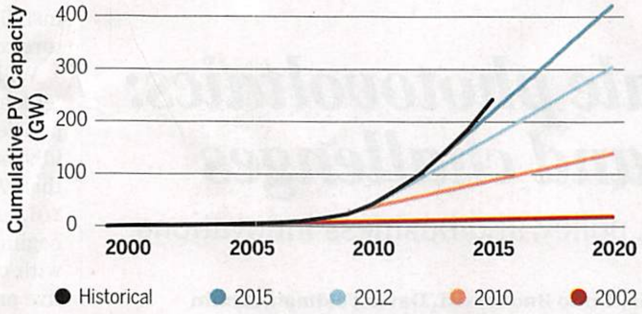
are extrapolated to ~5 TW. Some manufacturers will likely meet this type of pricing earlier than others. For example, First Solar recently laid out a roadmap to reach $0.25/W module production cost by 2020, and aggressive cost reduction targets are being pursued by most crystalline silicon module manufacturers.

Increases of module efficiency to 25% are quite plausible. SunPower's X22 series is specified to have a minimum total-area module efficiency of 22%. In 2016, Panasonic and SunPower announced record aperture-area efficiencies of 23.8% and 24.1%, respectively, for full-sized modules. Analyses also illustrate the substantial impact of decreasing degradation rate to 0.2%/year and increasing the system lifetime to 50 years. Degradation rates of <0.2%/year and lifetimes over 30 years have been reported in a variety of locations and products (*6*). Realizing benefits of longer lifetimes will require innovation in business models and financing.

The bigger challenge will be to achieve improvements in all these areas simultaneously to reach the $0.03/kWh target. If we consider technologies that have demonstrated efficiency in excess of 20%, the pathway to $0.03/kWh is likely to differ for each approach. Silicon, the market leader, is on a path to $0.30/W module price or even $0.20/W if the price trajectory remains below the historical curve. Higher efficiencies are being demonstrated using HIT (heterojunction with intrinsic thin layer), PERC (passivated emitter and rear cell), and IBC (interdigitated back contact) structures, as well as shifts to n-type wafers, passivated contacts, and other innovations. All indications are that the combination of >20% efficiency at a price of $0.25/W is a plausible contributor to a $0.03/kWh target for silicon systems without subsidies.

Cumulative PV installations

Projected (labeled by year of IEA publication) versus actual (labeled as "historical"). See supplementary materials for data sources and discussion.

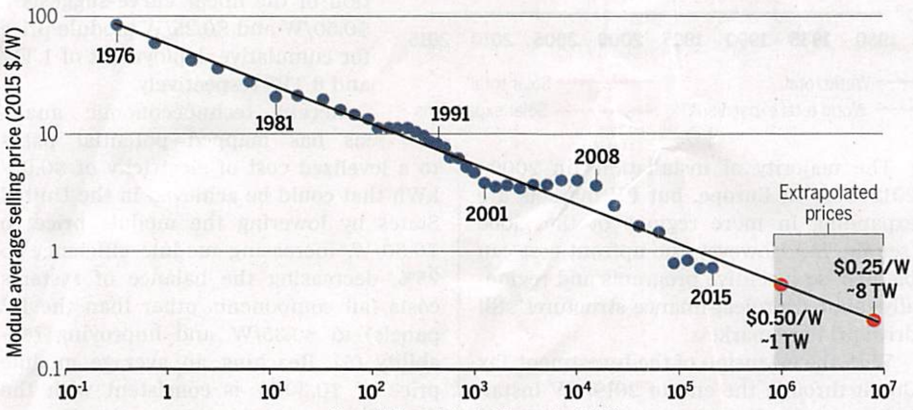


First Solar has demonstrated record cell efficiencies with cadmium telluride (CdTe) of 22% and is increasing module efficiency (record now is 18.6%), with a trajectory to surpass 20%. Recent research (*7*, *8*) has demonstrated photovoltages >1 V. If higher photovoltages can be realized, CdTe efficiencies in manufacturing can increase still further.

Copper indium gallium diselenide (CIGS) efficiencies and cost have been comparable to those of CdTe (record cell efficiency now 22.3%). Multiple companies are implementing CIGS into lightweight products that could replace roofing material or address other markets for flexible products. Further research is needed to optimize deposition of CIGS on flexible substrates to achieve highest efficiencies in production and to develop low-cost, durable packages.

PV module experience curve

Historically, module prices have decreased as a function of cumulative global shipments (blue dots reflect historical data, red dots reflect extrapolated prices for 1 TW and 8 TW based on the historical trend line). See supplementary materials for data sources.



GRAPHIC: N. CARY/*SCIENCE*

Concentrator PV modules using multijunction, III-V cells have demonstrated efficiencies in the range of 36 to 39%, with further research likely to push above 40%. Substantial development is needed to optimize system design and reduce cost. Scaling to the needed volume will require major commercial investment and research to understand critical design parameters.

III-V materials, such as gallium arsenide (GaAs), have achieved the highest efficiency of any single-junction technology (current champion is 28.8%) and have already demonstrated 24% efficiency for an 850 cm² module (*9*). Although these modules are very expensive, epitaxial lift-off techniques (*10*) enabling substrate reuse have been demonstrated. III-V modules have the potential to reach very low costs with higher efficiency and lower weight than conventional modules.

Research on perovskites has highlighted how materials can be engineered to be defect tolerant, reducing requirements on material quality and enabling ultralow-cost manufacturing technology for high-efficiency materials. These materials have caught the imagination of the PV community with their rapid rise in small-cell efficiency, increasing from 14.1% in 2013 to 22.1% in 2016. Lessons from perovskites may identify a new class of solar cells that can achieve efficiencies comparable to GaAs but with easily scalable manufacturing.

Although the rapid drop in prices has enabled faster growth, the current low module prices in the marketplace make it challenging to attract investment for development, scale-up, and market entry. Continued research and investment are needed in technologies that have potential to provide improved performance at competitive cost. Reducing factory costs will play a critical role in enabling manufacturing to scale up, to reach installations in the multi-TW scale over the next decade.

The ultimate test of a technology is the market. For PVs, as prices have dropped, the market has grown substantially. PV power-purchase agreement (PPA) prices have dropped by nearly 75% in the past 7 years (*11*). PPA prices below $0.05/kWh are common in the United States and are believed to be economically sustainable in sunny locations with low-interest project financing and low construction costs, whereas record bids for new projects in multiple countries have recently gone as low as ~$0.03/kWh.

COMPLEMENTARY TECHNOLOGIES

Grid-integration technologies and flexibility options available today should enable integration of at least 25 to 40% variable renewable energy (VRE), i.e., solar and wind, with feasible cost and stability (*12*). One major option for increasing flexibility of grids to accommodate VRE is demand-side management (DSM), which can shift load to times when there is excess electricity from VRE technologies. DSM could include preheating or cooling of water for buildings and leveraging their thermal mass to shift energy requirements to take advantage of electricity from renewables. Other methods that help grids accommodate more VRE include increased interconnected transmission, more flexible conventional generation, increased grid balancing-area cooperation, and better forecasting.

When the share of VREs rises above 30 to 40% or the grid is nonexistent or weak, then additional system-level factors must be addressed. In large grids, system inertia is provided by the rotating momentum of large synchronous generators, which allow the grid to ride through short-term system disturbances. VRE will need to provide "synthetic inertia" through fast-reacting power-electronic inverters. Inverters cannot provide the same level of short-circuit current as synchronous generators, which will require changing how the grid is protected for short circuits. Solutions include adding synchronous condensers or completely revising the approach to system protection.

Estimated compound annual growth rate (CAGR) required to reach TW-scale deployment in 2030

Analysis includes annual loss fractions per year of 0.02 (past capacity) and 0.04 (newly installed capacity). See supplementary materials for model details.

2030 TARGET (TW)	CAGR (%)	ESTIMATED TOTAL INSTALLED ANNUAL PRODUCTION CAPACITY IN 2030 (TW/YEAR)
3	15	0.5
5	21	1
8	27	1.9
10	29	2.5

GRAPHIC: N. CARY/SCIENCE

At high levels of VRE penetration, storage technologies will be required to bridge the gap between generation and demand. Electrochemical batteries have attracted considerable attention. The market for lithium (Li)–ion batteries has grown rapidly with the growth of the portable consumer-electronic device market. Reduction in Li-ion battery manufacturing costs is expected to continue (*13*).

The amount of storage needed at a particular price point is a function of the flexibility of the local grid, the value of PV electricity to the off-taker, and the value of other services that energy storage can provide. These determine the energy-storage demand curve for each market—but, in general, a price target of ~$150/kWh has been viewed as sufficient to enable substantial market growth. If we assume that this target can be met by 2030, with 6000 charge-discharge cycles (*14*), a first-order approximation would suggest a round-trip (charge-discharge) stored-electricity price of less than $0.025/kWh by 2030. Even if one doubles this cost to account for additional financing, installation, and power conditioning costs, dispatchable solar electricity (PVs at $0.03/kWh plus storage at $0.05/kWh) could be economically competitive for a range of markets by 2030. New market structures that monetize the value of storage will need to be considered to realize the full potential.

With new controls and innovative market structures, batteries in electric vehicles (EVs) and plug-in hybrid electric vehicles (PHVs) could act as a flexible load but also feed power back when connected to the grid, which can further ease VRE grid integration. Some forecasts suggest that EVs will become economically feasible in the 2020s and predict ~400 million EVs on the road by 2040 (*15*). Terawatts of storage capacity could thus be available by EVs alone.

PVs naturally provide electricity, but they can also provide a path to fuels for transportation, as well as process heat. Power-to-gas can use renewable energy to create hydrogen via electrolysis. To become feasible as storage, power-to-gas technologies need sizable cost reductions. Energy storage in the form of gas or fuel is expected to play a substantial role in future energy systems.

TRAJECTORIES TO TW DEPLOYMENT

PV shipments in 2015 were about 57 GW (*16*). Using this starting value and assuming a 25-year lifetime, we estimate challenging but feasible growth rates to reach 2030 target installed capacities of 3 to 10 TW (see the table). The growth rates are all substantially below what the industry has achieved over the past decade.

The PV industry is on a trajectory to reach at least three TW of cumulative PV installations by 2030. Challenges that need to be overcome to reach 5 to 10 TW of PV by 2030 include (i) reduce cost and improve performance of PV; (ii) reduce cost and time required for expanding manufacturing and installation capacity; (iii) move to more flexible grids that can accommodate high numbers of PVs; (iv) increase overall demand for electricity by increasing the electrification of transportation and heating and cooling; and (v) pursue synergistic breakthroughs in storage, solar fuels, chemical production, desalination, and all forms of solar conversion.

Meeting these challenges will enable a viable trajectory for solar energy to provide a substantial fraction of the world's energy needs. Almost 200 years after Becquerel's discovery of the PV conversion of light to electricity, the realization of this vision is both more urgent than ever and within our grasp.

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SUPPLEMENTARY MATERIALS

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BOOKS *et al.*

SCIENCE AND SOCIETY

Embracing the unqualified opinion

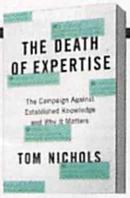
A pair of timely tomes probes the factors converging to undermine the expertise of scientists, scholars, and trained professionals

By **Sheril Kirshenbaum**

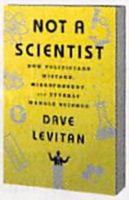
Given the rise in fervent opposition to facts and ongoing political assaults on scientific integrity, it's no surprise that Oxford Dictionaries selected "post-truth" as 2016's international word of the year. Populism coupled with renewed anti-intellectualism has affected leadership at home and abroad, leading to geopolitical instability. The ramifications for the science community are yet to be understood, but federal research priorities, funding, and innovation may be affected for decades. Two timely new books take different approaches toward grappling with the dangerous disconnect between expertise, policy-makers, and the public that threatens to undermine scientific progress for the foreseeable future.

Tom Nichols's *The Death of Expertise* is a meticulously researched expansion of his 2014 article of the same name, published by *The Federalist*. In it, he argues that widespread public doubt of experts has become a persistent problem, along with the expectation that the opinions of nonexperts should have level footing in debate.

The Death of Expertise
The Campaign Against Established Knowledge and Why It Matters
Tom Nichols
Oxford University Press, 2017. 268 pp.



Not a Scientist
How Politicians Mistake, Misrepresent, and Utterly Mangle Science
Dave Levitan
Norton, 2017. 270 pp.



The Internet has had a primary role in this phenomenon, equalizing access to knowledge and leading the public to mistakenly believe that their opinions are as valid as those of trained experts. Our high-pressure, hypercompetitive modern media environment compounds the problem, producing sound bites over real analyses. Nichols also places some of the blame on American universities that have made higher education a commodity, producing overconfident, yet underskilled, graduates.

Complicating matters, experts are not always effective communicators and are not infallible, meaning that the public is frequently confused by uncertainty or predictions that turn out not to be true. This has fueled antivaccination groups, climate change denial, fear of genetically modified foods, and more.

According to Nichols, human psychology plays a role as well. For example, due to a phenomenon known as "confirmation bias," we readily find and accept evidence that supports our preexisting beliefs. The result, he argues, is that corroding "trust among experts, citizens, and political leaders" has tainted politics and undermined democracy.

Nichols calls President Donald Trump's road to the White House "a one-man campaign against established knowledge," quoting the 45th president of the United States: "They say, 'Oh, Trump doesn't have experts.' You know, I've always wanted to say this.... The experts are terrible. They say, 'Donald Trump needs a foreign policy advisor.' ... But supposing I didn't have one. Would it be worse than what we're doing now?" Such attacks on expertise resonated widely with the American public, tapping into the popular belief that experts and intellectuals are working against the best interests of ordinary citizens.

Dave Levitan's *Not a Scientist* zeroes in specifically on science in politics and the

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The reviewer is the coauthor of Unscientific America: How Scientific Illiteracy Threatens Our Future *(Basic Books, New York, 2009). Email: sheril.kirshenbaum@gmail.com*

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