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News & Highlights

Perovskite Pushes Solar Cells to Record Efficiency

Sean O'Neill

Senior Technology Writer

The future has grown brighter for solar power, with the setting of a new world record for the efficiency of a silicon/perovskite solar cell in December 2020. Made using a layer of silicon in tandem with a thin-film layer of synthetic perovskite, the cell had an area of 1.12 cm^2 and was certified in independent testing by the US National Renewable Energy Laboratory (NREL) in Golden, CO, USA, to be 29.52% efficient [1]. Plainly put, the tandem cell was able to convert nearly 30% of the simulated sunlight shining on it into electricity.

The cell, and the perovskite technology that enabled the record, was developed by Oxford PV, based in Oxford, UK. The company is currently commissioning a production line in its factory in Brandenburg an der Havel, Germany, to make the world's first commercial perovskite/silicon cells, 156 mm to a side, with an efficiency of about 26% (Fig. 1). When they become available, expected in early 2022, they will be the most efficient commercially available solar cells in the world—industrially produced silicon solar modules are currently hitting efficiencies of 20%–22%.

"We started looking at perovskites ten years ago, trying to find materials that were fundamentally cheaper to process than silicon," said Henry Snaith, co-founder and chief scientific officer at Oxford PV, and professor of physics at the University of Oxford. "This basically involved using solution or sublimation-based processes. We wanted materials that did not require 2000 °C to crystallize. We had this long-term goal and belief that one day we would get to 10% efficiency, and literally the first cell we made with these perovskites was 6.1%, breaking our all-time lab record. This seems pretty paltry today, but at the time it was like, wow, this stuff works right out of the box."

Perovskites in solar photovoltaics (PV) are a timely development because decades of improvement in silicon have left it bumping up against fundamental constraints on its efficiency; PV materials all have a characteristic limit on how much sunlight they can convert to electricity. The limit depends on their "bandgap"—the energy required to unbind an electron from the material, enabling it to become a charge carrier and move around a circuit. The bandgap of crystalline silicon is 1.1 eV, which means photons from the sun with less energy than 1.1 eV cannot free an electron, while photons with higher energy can still generate a charge carrier, but the photon energy in excess of 1.1 eV is wasted as heat.

Taking the spectrum of sunlight into account, the theoretical efficiency limit of perfect silicon is about 32%. However, from 1954 when the first practical silicon solar cell was made by Bell Laboratories in the United States [2], the achievable efficiency in the laboratory is topping out at around 27%.

Fig. 1. An array of Oxford PV's tandem silicon/perovskite solar cells, manufactured at Oxford PV's facility in Brandenburg an der Havel, Germany. The company's first commercial cells, available in 2022, will have an efficiency of 26%. Credit: Oxford PV, with permission.

Synthetic perovskites are materials that share the same crystal structure as the naturally occurring mineral perovskite, calcium titanium oxide. Synthetic perovskites burst onto the solar PV research scene in earnest in 2012, when their potential application to solar cells gained wide attention [3]. Those used today are typically organic–inorganic metal halide perovskites, with the metal either lead or tin. "Metal halide systems are just exquisite at how they do the PV task, and that makes them really compelling," said Joe Berry, a principal scientist at NREL who leads its Perovskite and Hybrid Solar Cells team.

A thin perovskite film, layered on top of a silicon cell, can be engineered to have a bandgap of 1.7 eV—a band gap that complements silicon's lower bandgap [4]. This means more photons are captured from more of the sun's spectrum, freeing more electrons to generate more energy. The theoretical efficiency limit when combining these materials is 43%. "You can never reach that last bit of theoretical efficiency," said Chris Case, chief technology officer at Oxford PV. "The practical efficiency is going to reach the high 30 s, but we believe we can take our commercial cell all the way to 33% just on our current knowledge set."

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The looming jump in PV efficiency comes at a time when solar was already an attractive proposition for energy companies, from both the financial and ecological standpoints. In many countries of the world, utility-scale solar PV is now typically cheaper than new coal or gas-fired power plants [5]. In 2018, the Intergovernmental Panel on Climate Change (IPCC) warned that limiting global warming to 1.5 °C would require "rapid and far-reaching" transitions in energy generation, among other things, because human-caused CO_2 emissions will need to reach "net zero" by around 2050. The International Renewable Energy Agency (IRENA), an intergovernmental organization based in Abu Dhabi, United Arab Emirates, that supports countries transitioning to a sustainable energy future, has projected a climate-resilient energy transition pathway in line with the IPCC—called the renewable energy roadmap (REmap) Case—that sees solar PV as the dominant power source in 2050, with 8.5 TW of installed capacity worldwide, with wind power in second place (Fig. 2) [6].

Solar PV is already accelerating. In the United States, for example, it accounted for 43% of all newly installed generating capacity in 2020, putting it first among all energy-generating technologies for the second year in a row. Over the next ten years, the US solar industry is expected to quadruple its current capacity [7]. Part of this boom is a result of the surprising speed at which cost of solar PV technology has dropped over the last decade. With currently available solar cell efficiencies having risen to around 20%, and the associated hardware costs falling, there was an 82% drop in the installed cost of utility scale PV systems between 2010 and 2020 in the United States according to NREL [8]. The trend is similar across the world (Fig. 3) [6].

At the end of 2020, global solar PV capacity stood at about 710 GW, up from 581 GW in 2019 (Fig. 4) [6]. Growing this capacity deep into the terawatt scale will require rapid acceleration of solar PV production, meaning that the materials required must be in abundant supply. This is another benefit of perovskites, as they typically are produced in films about 0.5 μm thick and made of easily sourced materials. Oxford PV notes that 35 kg of perovskite can be used to generate the same amount of power as 7 t of silicon—which is typically used in wafers 160 μm thick—and suggests that the material could one day replace silicon altogether [1].

A key difficulty in the scale up of other, established, thin-film solar technologies is that they are based on either cadmium telluride or copper indium gallium selenide. Besides concerns over the toxicity of cadmium, that element, along with tellurium and indium, is too rare for these technologies to viably scale to terawatt levels [9].

Metal halide perovskites, in contrast, can be made from abundant materials, and inexpensively. "They really are amenable to a number of high-throughput, low-cost processing routes," said Berry. "There are a lot of ways to make things cheaply and make them poorly, but you can process perovskites in ways that do not compromise the fundamental material properties that you were after to begin with. And perovskites also have some really unique advantages—there are demonstrated schemes to recycle them at very high efficiency."

But it is not all good news. For now, the most efficient perovskites contain lead, though with this being thin-film technology the amount present is relatively low. A more pressing challenge to the wider adoption of silicon–perovskite tandem solar cells is their long-term stability. Utility scale PV panels are required to last for about 25 years. Perovskite technology has advanced rapidly since they were first applied in PV cells, but their long-term stability is not yet established.

Unlike silicon, perovskites are ionic materials and more prone to degrade, especially if they become moist, so effective encapsulation of the perovskite film is crucial. Oxford PV, which holds more patents related to perovskite solar PV than any other organization [10], is confident of their engineering process and perovskite encapsulation method. "We have expended a lot of effort over the last decade, changing the composition of the perovskite, the materials, the device's structure, and it has all been about enhancing the stability," said Snaith. "The efficiency just came without effort; achieving stability has required the most work. But now

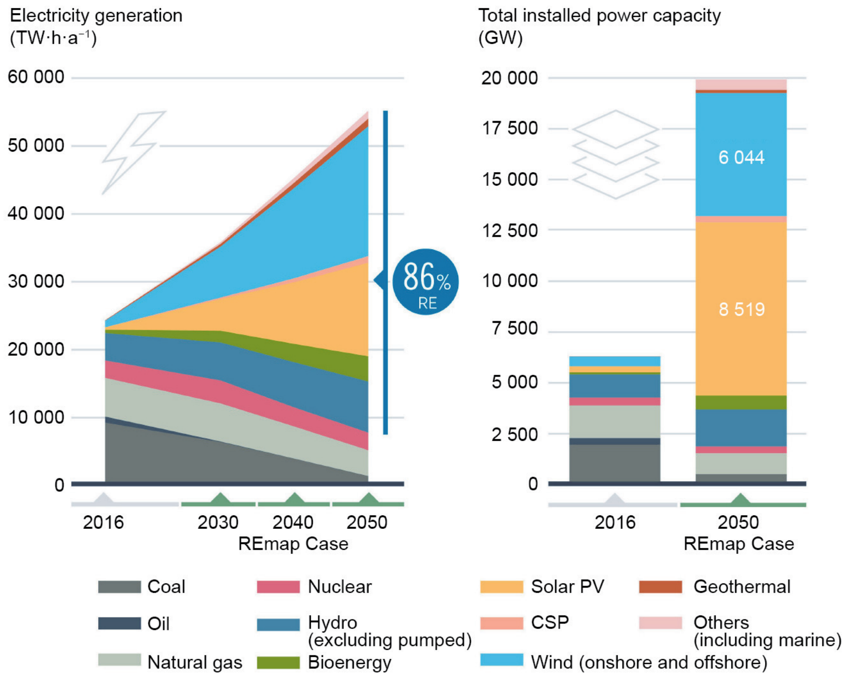

Fig. 2. Projections of the shift towards cleaner, renewable energy that will be required to reduce emissions fast enough to meet the IPCC targets on climate change and take the planet to "net zero" CO_2 by 2050 [6]. RE: renewable energy; CSP: concentrated solar power. Credit: ©IRENA, with permission.

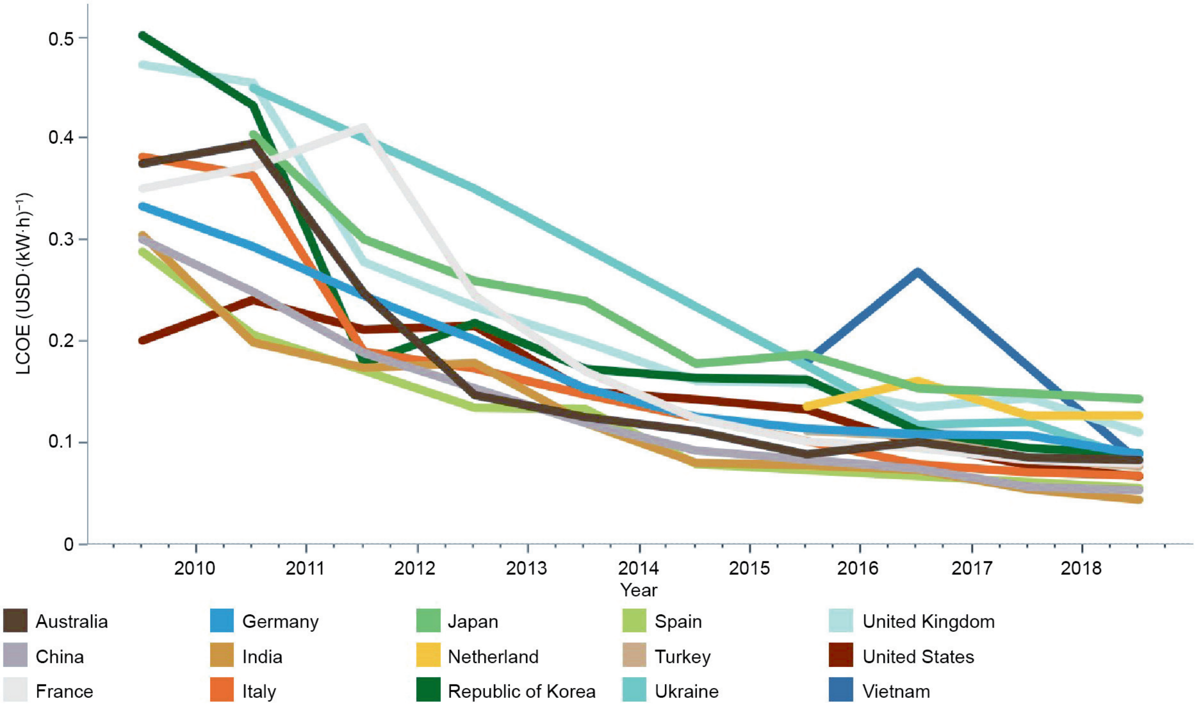

Fig. 3. The levelized cost of energy (LCOE) of newly commissioned utility-scale solar PV projects by country has dropped sharply in the past decade [6]. The LCOE is the minimum average price at which electricity must be sold—over the lifetime of a given solar project—for it to break even financially. Credit: ©IRENA, with permission.

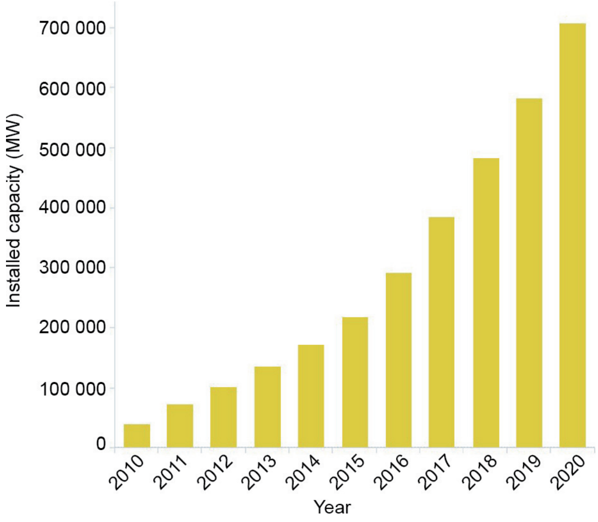

Fig. 4. Total global installed capacity of solar PV has grown sharply over the last decade and shows every sign of increasing exponentially [6]. Credit: ©IRENA, with permission.

we are extremely confident on the efficiency, and the stability of our technology is set."

The wider industry and scientific community is also coming together to address the issue of stability. In 2020 an international collaboration of researchers, including Berry and Snaith, united to produce a consensus statement for stability assessment and reporting for perovskite PV [11]. "We are trying to get to the place where we understand these perovskite materials well enough, in the decade that they have been around, so that we can make 30 year predictions. This predictive science is really technically demanding, but the issues that we have seen so far are not show-stoppers at a fundamental materials level," said Berry. "It then becomes a question of what technical solutions you have got and how much you can reduce the cost—these kinds of business things."

Adding a perovskite-application step to solar PV production will carry a cost and how this will impact the market is uncertain. The likely price of Oxford PV's commercial cells has not been revealed. In large-scale energy generation, the levelized cost of energy (LCOE), the minimum average price at which electricity must be sold—over the lifetime of a given solar project—for it to break even financially, is a key factor. Any potential increase in initial price for this new technology will be weighed against the promised drop in LCOE that greater efficiency brings.

Oxford PV's manufacturing plant is currently being commissioned at 100 MW annual capacity, with the goal to scale up to 10 GW per year by the end of the decade, a modest goal for a solar sector adding about 120 GW of capacity annually. Other commercial organizations also developing perovskite PV technology include the major Japanese firms Panasonic and Sekisui Chemical Company, the Chinese companies Microquanta Semiconductor and WonderSolar, the Republic of Korea's Frontier Energy Solution, and Saule Technologies in Poland [12].

Perovskite technology has grown rapidly in the last decade. How fast commercialization will move from here is speculation, but Snaith suggests the global uptake and widespread use of silicon–perovskite solar cells will take at least another ten years. Beyond that, he said, the use of perovskites also presents some tantalising additional possibilities. "Perovskites can be made very thin and on very light substrates, so it can be made bendable or flexible. And in the future, we will get solar PV efficiency up to 40%, so cladding electric vehicles starts to make sense as it will make a measurable impact on charging. Similarly, if we can develop lightweight solar foils, we can think about cladding commercial buildings."

In 2020, the US Manufacturing of Advanced Perovskites Consortium was pulled together with the stated goal to "regain US dominance in optoelectronic and photonic manufacturing" [13]. The organization was formed by NREL, the Washington Clean Energy Testbeds at the University of Washington in Seattle, the

University of North Carolina at Chapel Hill, and the University of Toledo in Ohio. The consortium includes six domestic commercial industry partners [13], including First Solar, a Tempe, AZ-located major producer of utility-scale thin-film solar PV based on cadmium-telluride technology.

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