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PRINCETON UNIVERSITY

Welcome to the Solar Distillate

Robert Socolow, August 2017

Five years ago, Princeton University started producing electricity from a large solar installation on campus. Some of us were led to ask what could be learned about solar power in general from Princeton University's project: What costs and public policies did the university confront? What technologies were chosen? How common are solar projects of its scale? The resultant report, *Sunlight to Electricity: Navigating the Field,* answers these questions, but it goes much further. Its principal focus is on the large, generalizable issues that we believe will determine how important solar power becomes, globally.

We call our report a "Distillate," and it is the fourth in a series of Distillates written for Princeton's Andlinger Center for Energy and the Environment. The Distillates are designed to provide succinct yet substantive information to policymakers, educators, students, and other citizens. The Distillates are linked in that each surveys a single technology that may have the potential to contribute significantly to a much modified global energy system responsive to the threat of climate change.

Each Distillate introduces the relevant science, technology, economics, and public policy. It is written for a reader who is new to the field, and it emphasizes pedagogy throughout. Our target reader likes quantitative thinking but knows very little physics and chemistry. In this "Solar Distillate" we describe how the Sun moves through the sky, how incident sunlight becomes solar power, and how incentives have helped solar power compete in electricity markets. We have tried neither to advocate for solar power nor to be dismissive of its potential. Our goal is to make critical issues accessible.

Currently, solar electricity accounts for approximately one and a half percent of total global electricity. One and a half percent is a big number and a small number. It's big, looking back: 10 years ago there was 50 times less installed capacity to produce solar power on the planet than today. It's small, when solar power is compared to other electricity sources today: it is in sixth place, far behind; in front are coal, natural gas, hydropower, nuclear power, and even wind (which currently accounts for about three times more global electricity). So far, solar power's expansion has not slowed down. In 2016 alone, the installed capacity to produce solar power grew 30 percent globally, 60 percent in the U.S., and 80 percent in China, which now has about twice as much installed solar capacity as any country in the world. The U.S., Japan, and Germany are in a three-way tie for second place. How long can such rapid growth be sustained?

Two issues bubble to the top for their importance to solar power's future: Will future expansion continue to feature both centralized and distributed generation, or will one form of generation begin to crowd out the other? And how severely will solar power's fateful intermittency challenge the management of electric grids? As a preview of the Distillate, we offer a short discussion of each issue here.

The role of distributed generation

The largest solar installations today are about 100,000 times larger than the installations on the rooftops of private homes: contrast 10 linked panels on a roof to a million linked panels in a Nevada desert. Yet at all scales the solar panel is the same: no other energy technology is as modular. Princeton University's project is an example of a mid-scale installation, roughly a thousand times larger than a rooftop project and a hundred times smaller than the world's largest projects.

An intriguing question is the future balance of large and small installations. The future solar power market could take the form, nearly exclusively, of monster solar farms built on cheap land and connected to users by a network of long, utility-owned transmission lines. Such a future continues the electricity system as we know it now: the solar power plant fits right in with the other large plants that burn coal or natural gas, the hydropower plants, and the nuclear plants. Alternatively, solar power could be dominated by what is called "distributed generation": millions of small solar electricity facilities on the roofs of homes and schools and warehouses, and in open fields on public and private land.

There are economic arguments for both outcomes. Large solar facilities compete in wholesale power markets; rooftop solar competes in retail markets. It is more expensive, per panel, to put a panel on a roof, but the power is worth more there. Costs in both markets are falling, and both markets are strongly affected by incentives – also called subsidies – that are shrinking. (Beware: what solar advocates call "incentives," those critical of solar power call "subsidies.") Will centralized solar power drive out distributed generation? Specifically, will Europe connect to centralized solar power in the Sahara? Will Texas develop distributed generation?

The Figure shows electricity production on an August day in 2016 for the State of California. Separated out are distributed and centralized solar electricity production, as well as electricity from wind, Over that particular day, distributed solar production was about half as large as centralized solar production. These ratios are not usually reported.

Many solar advocates today are intensely committed to distributed generation. In their view, especially if accompanied by the parallel expansion of distributed energy storage, distributed energy brings self-reliance, a more resilient network than the current electric utility grid, the integration of solar power and by-product heat into architectural design, and the strengthening of communities. They have no affection for monster solar farms. How important will this preference prove to be, if cost-savings for centralized production achieved through economies of scale remain so substantial?

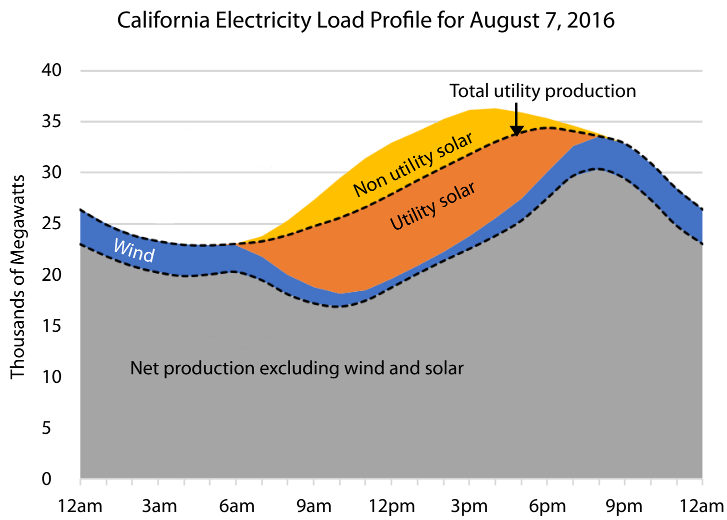

Figure: Total electricity production for California users from all sources, including distributed solar facilities in California, on August 7, 2016. From bottom to top, the lowest (gray) region represents production from all sources aside from wind and solar. The next (blue) region is wind generation, and the region above it (orange) is utility solar generation. The top-most (yellow) region is customer-owned ("non-utility") solar power. Adapted from: Paulos, Bentham, 2016 "California has more solar power than you think – a lot more." Greentech Media, http://www.greentechmedia.com/articles/read/california-has-more-solar-than-you-think.

Accommodation to intermittency

On a sunny day, the solar electricity produced by a south-facing panel in the U.S. peaks at midday, rises rapidly toward that peak in the morning, and falls rapidly in the afternoon. Aggregate demand for electricity, however, usually peaks in the evening. To provide the evening electricity, other power sources must ramp upward, as solar power output falls. And at mid-day, other power sources must shut down.

As solar power grows, the rest of the system changes. Electricity produced from natural gas benefits, because natural gas power plants, which resemble jet engines, can vary their output quickly. Nuclear and coal-based power plants lose ground, because they run poorly when unable to produce electricity at a constant rate. To date, the critical role of natural gas in fostering intermittent renewables is unheralded: neither the solar power industry nor the natural gas industry acknowledges how well they fit together.

Progress in energy storage (think, batteries) is critical to the future of solar power. For example, the noon-to-evening mismatch can be addressed by charging batteries with some of the extra solar electricity produced at noon, then discharging the batteries in the evening. Storage is useful, whether distributed or centralized solar power dominates a grid, since the time profile in both cases is nearly the same.

A third strategy to address intermittency, alongside investments in compensating energy sources and energy storage, is to modify demand. Governments can make electricity cheaper at noon than in the evening, for example. Large industrial consumers already face "time-of-day" pricing. As homeowners, shop keepers, and others begin to face similar pricing, new businesses will emerge that will install "smart" devices on air conditioners, water heaters, and other appliances that automatically minimize operating costs.

In one meaning of "smart," the objective is to eliminate human engagement: no one will do anything different because it is a cloudy day. Personally, I wonder whether this might be the wrong goal. Once upon a time, people waited for a sunny day to dry their clothes outdoors. Might many people welcome, or at least accept, a life-style that recovers some consciousness of the hour-by-hour and day-by-day variations present in nature? If so, an electricity system that accommodates solar power's intermittency will face lower hurdles.