Article 1: Overview

The goal of this Distillate is to enable the reader to understand the state of solar energy today and to develop his or her own views of some of the key issues that loom over solar power's future.

Today, for the first time in human history, a commercially significant quantity of solar energy is being turned directly into electricity. Global capacity to produce solar electricity was about 50 times greater in 2016 than 10 years earlier. Solar power has grown rapidly in Europe, Asia, and North America.

No one knows how long future solar growth will resemble the past. It is conceivable but far from certain that solar power will dominate the global electricity system by mid-century. There is still a long way to go. In 2016 only about 1.5 percent of total global electricity came from solar power. In the U.S. the percentage was nearly the same, even though one million U.S. homes have solar panels on their roofs and several of the world's largest solar installations are in the deserts of the southwestern U.S.

This Distillate explores five open questions related to solar power's future:

1. *Will distributed and centralized deployment both flourish?* Solar cell technology is spectacularly modular: a solar cell will convert sunlight into electricity whether on a rooftop or in a multi-thousand-acre field, and assemblages of these cells are housed in panels that are essentially the same wherever they are used. Due to this modularity, the plummeting costs of solar cell technology have had a dramatic, positive impact on the growth of solar power at all scales. Future deployment could tilt toward very large projects because of economies of scale: large projects have substantially lower construction costs than small projects, for the same amount of electricity generated. However, distributed electricity generation, especially if accompanied by distributed electricity storage, may enable innovative grids that are more flexible and resilient than the centralized grids of the past. If deep penetration of distributed solar generation into electricity markets is achieved, political support for pro-solar policy will strengthen, to the likely benefit of centralized solar power as well. The path forward may well feature parallel development at large and small scale – with much geographical variation in the mix of the two scales.
2. *How much can balance-of-system costs be reduced?* The principal challenge of past decades was reducing the cost of the solar cell and the solar panel that houses the cell. Now, "balance-of-system" costs are emerging as the principal cost concerns. The balance of system, here, is all of a solar power project except for the solar panels: the land, the structure that holds the panel, any tracking hardware, the inverters that change the direct current (DC) produced by the cell into the alternating current (AC) required by the user, installation at the site, interconnection to the grid, and business costs such as financing, permitting, and insurance.
3. *Will crystalline silicon remain the workhorse of solar power?* Today, crystalline silicon has 90 percent of the solar cell market. Can any of the new thin-film technologies challenge silicon's dominance, now that the silicon cell industry has developed so much infrastructure and experience? The crystalline silicon solar cell has the limitation (thus far) of being available only as a rigid structure, which limits potential applications. Its competitors are thin films, whose versatility assures that there will be at least niche markets for some of them, even if they do not become significant producers of solar electricity. To enter the market, a thin film will need to convert sunlight to electricity at substantially higher efficiency than the crystalline solar cell, demonstrate stability and ease of manufacture, and avoid scarce or toxic materials.
4. *Will solar power subsidies disappear?* Government policies favorable to solar electricity are called "incentives" by their proponents and "subsidies" by their detractors. Subsidies have enabled solar energy to mature, and now they are shrinking, both for centralized and distributed generation, as solar power becomes increasingly competitive. The system costs of incentives for distributed generation were small when they were paid only to "early adopters," but as the fraction of beneficiaries in an eligible group grows, the non-adopters bear more noticeable costs and push back.

On the other side of the argument, those who favor incentives stress their direct environmental benefits, including cleaner air and less rapid climate change. Specific to distributed generation, they also note that producing electricity closer to the point of use, especially in combination with dispersed electricity storage, can reduce grid congestion and improve system performance.

5. *Will the intermittency of solar power soon throttle its expansion?* The full system in which the solar panel is embedded consists not just of the panel and the balance of the system at the project level, but also the electricity grid that must accommodate an intermittent and only partially predictable supply. Grid regulators and operators are able to accommodate the intermittency and unpredictability inherent in solar power when its market share is tiny. However, in an increasing number of places and increasingly often, solar power is now raising grid-management problems resulting from oversupply at mid-day, as well as rapid output gains in the morning and losses in the evening.

   Compensating responses are emerging. The grid can be made more accommodating by reducing the presence of nuclear and coal power plants, which function best when running at a constant rate, in favor of hydropower and gas-turbine power, whose output can be varied rapidly. The grid can make greater use of centralized and distributed electricity storage and can be extended geographically to integrate distant sources that have complementary time profiles. Time-of-use pricing can be more aggressively implemented to induce shifts in supply and demand by several hours. The choice of compass orientation for some stationary solar collectors in the northern hemisphere will then become southwest instead of due south, flattening the peak at noon. People will become more aware of whether a day is sunny or cloudy as they find themselves washing their dishes (and, perhaps, charging their electric-car battery) preferentially at mid-day on sunny days.

   Intermittency has been relatively invisible thus far, even though intermittency is arguably the Achilles heel of solar power, hobbling its path forward. Indeed, a widely cited objective for solar power, "grid parity," neglects intermittency. Solar energy achieves nominal grid parity when the cost of a kilowatt-hour of solar energy is the same as a kilowatt-hour from, say, natural gas or coal. But this takes no account of solar power's limited ability to produce power when desired, and therefore its higher grid-integration costs.

Roadmap

We have endeavored to treat technology and policy with equal seriousness. We have written for the reader who has little technical background but an appetite for scientific argument and curiosity about the policy domain. Discussions of technology and policy are in separate articles, however, so as to enable readers to read selectively if they come to the subject with a stronger interest in one than the other.

The four articles in this Distillate that follow this *Overview* (Article 1) address the five questions above, and they go considerably further. Article 2, "The Solar Panel: Key Concepts and Vocabulary," introduces the quantitative concepts widely used to discuss the deployment of solar power and to measure the performance of solar projects in physical and economic terms.

Article 3, "*From the Sun to the Solar Project*," deals with the first of the five questions above by comparing projects at various scales. It calls attention to the prominence of "mid-scale" projects on the rooftops of commercial buildings, in public parks, and in other settings, much larger than projects on the roofs of homes but similarly not owned by electric utilities. It also discusses the second question, balance-of-system issues. Prior to dealing with these questions, Article 3 describes the massive amount of energy arriving from the sun and then provides views of solar power's deployment at descending geographical scales: planet, country, state, and individual project.

Article 4, "*Solar Cell Technology*," illuminates the third question, the dominance of crystalline silicon. It describes many of the technologies used to convert sunlight into electricity, both currently commercialized and on the technological frontier, highlighting features that affect their competitiveness.

Article 5, "*Grid Integration and Policy*," takes on the fourth question (subsidies), with an emphasis on the U.S. and the state of New Jersey. Although New Jersey is atypical in the extent to which solar energy has been promoted by the state government, many other states have adopted similar policies and are confronting similar controversies. Article 5 also explores the critical fifth question (intermittency), describing its current emergence as a priority for the electric grid and the variety of partial responses in view.

The Distillate concludes with a brief appendix that presents some illustrative results from Princeton University's own solar project, which was the initial springboard for our report. Indeed, this Distillate generalizes what we learned from that project's technology choices, the many projects in New Jersey that it resembles, and its interactions with New Jersey and federal incentives.

Missing from our Distillate are several important issues. There is almost no discussion of the world's many giant solar projects (nearly all of them thousands of miles from New Jersey), and solar power at all scales in China, India, and elsewhere in the developing world.

Regarding technologies, this Distillate considers only flat-panel solar photovoltaic (PV) technology. It excludes "concentrating solar power,"[1] which is a second, currently competitive large-scale (but not rooftop) solar electricity technology. Also excluded are direct solar power for water heating and cooking, applications that are expanding rapidly in the developing world.

[1]Concentrating solar power (sometimes called "solar thermal" power) uses mirrors to focus sunlight and heat a fluid (liquid or gas) to a high temperature, whereupon the hot fluid powers an engine to produce electricity. In one version, sunlight is focused on long tubes running along the axis of parabolic troughs; in another, sunlight is focused onto a small spatial region at the top of a "power tower."