Appendix: The Princeton University Solar Project

Many of the general issues discussed in the five articles of this Distillate are illustrated here with specific reference to one project that the authors know intimately—the Princeton University solar project. The project produces 5.4 megawatts of peak power and occupies 25 acres (10 hectares) of university land. It has been operational since September 2012 and has been meeting approximately 5 percent of the university's annual electricity consumption. Figure A-1 shows an aerial view of the project.

Photo by Tom Grimes.

Figure A.1 Aerial view of the Princeton University photovoltaic field. The northern-most and western-most solar panels that appear darker are fixed-tilt panels; all of the others are tracking panels.

Princeton University is allowed to sell to the grid the solar electricity it generates at its mid-scale field. However, such sales practically never happen. The electricity used by the buildings served jointly by the university's solar electricity system and the utility nearly always exceeds the output of the university's system. On rare weekends in the spring, demand is low enough and the university's solar supply is high enough for the university to be able to export electricity, but in the first 2.5 years after the university's project started to produce electricity, only about one three-thousandth of the university's solar electricity was sold to the grid.

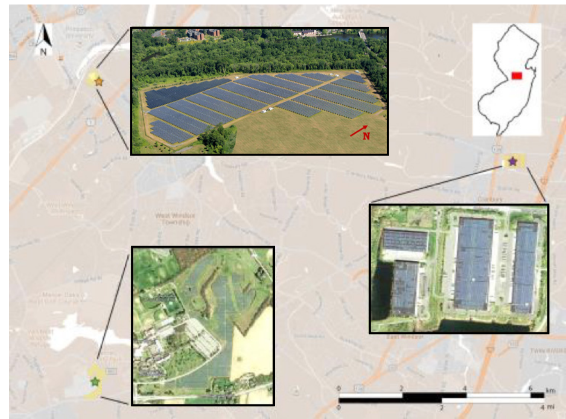

Figure A.2: Three mid-scale projects in central New Jersey: a ground-mounted system at Princeton University (top left, 5.4 MW), a ground-mounted system at Mercer County Community College in West Windsor (bottom left, 8 MW), and a system on the roofs of warehouses in an industrial zone in Cranbury (center right, 5.7 MW). The red rectangle in the upper right inset shows the location of the background map (10 miles by ten miles) within New Jersey. The photos of the Princeton University and Cranbury sites have the same scale; the photo of Mercer Community College site has been shrunk relative to the other two.

The university's project is the 37th largest solar project in New Jersey by capacity. A sense of the spatial density of large mid-scale projects in central New Jersey is conveyed in Figure A.2, which shows the Princeton project and the two other mid-scale projects of comparable size in the same area, 10 miles by 10 miles. Princeton's project is shown in at the top left. At bottom left, an 8-megawatt installation sits between Mercer County Community College's West Windsor campus and a large park. It is a joint endeavor between the college, the Mercer County Improvement Authority, and SunLight General Capital, LLC.[28] At center right, is a 5.7 megawatt project that has placed panels on the roofs of four adjacent warehouses.

[28]http://apps3.eere.energy.gov/greenpower/news/news_template.shtml?id=1856

Panels and Mounts

The Princeton University panel has 16,500 photovoltaic panels. 80 percent of these panels are mounted to provide single-axis tracking (lighter areas in Figure A.1) and the rest have fixed-tilt mounts (darker areas in Figure A.1). Decisions about where to locate the two mountings were driven largely by the shape of the available parcel of land.

The tracking panels are arrayed in rows that move like a seesaw, with the seesaw mount oriented north and south. The compass at the top-right of Figure A.1 confirms this orientation: each of the thin rectangles is one of these seesaws, rotated maximally to the east at sunrise, flat at noon, and rotating toward the west throughout the afternoon. As for the fixed-tilt panels, they face south, making at a 25 degree angle with the horizontal.

The tracking panels are further apart than the fixed panels, because the spacing required to avoid the shadowing of one panel by another is larger for tracking than for fixed panels. The tracking panels occupy approximately three times as much land area as the total active surface area of the panels, and for the fixed panels the multiplier is less, two instead of three.

The panel chosen for the Princeton University project has 96 monocrystalline silicon cells in an 8x12 array, roughly 1.0 meter by 1.5 meters in size. The panel's rated peak power output is 327 watts, the product of 6.0 amps of current and 54.7 operating volts.

Distribution of Initial Construction Costs

The total construction cost of the Princeton University project was approximately 30 million dollars, or about six dollars per watt. This cost is disaggregated in Figure A.3. The PV modules themselves account for 30 percent of the total, and balance of systems costs account for 70 percent. Non-panel hardware accounts for 16 percent; included are tracking equipment, inverters, transformers, mounting structures, motors, concrete, and fencing. There are also substantial site-specific costs, 12 percent of the total, as is usual for large, ground-mounted systems. The location of the solar field across a lake from the main campus electrical substation to which the solar field is attached mandated the placement of a 13 kilovolt cable (Figure A.4) in a conduit under the lake that lies between the solar field and campus. Other costs, including labor, project management, and permitting, account for the remaining 41 percent.

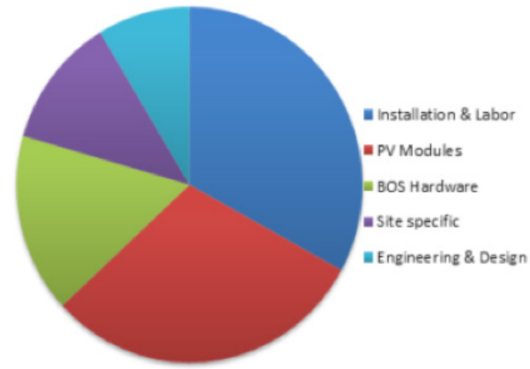

Figure A.3: Cost breakdown for the installation of Princeton University's 5.4-megawatt solar field completed in 2012. BOS is "balance of systems." The total cost was about 30 million dollars.

Figure A.4 Photo shows a cross section of the 13 kilovolt cable that connects the solar field to main campus and which passes underneath Lake Carnegie.

Variability at Various Scales

Variability in the project's electricity production at various time scales can be documented with the help of the detailed performance data that Princeton University is recording.[29] We distinguish four time scales here: seasonal variability, day-to-day variability, variability during the day, and variability in minutes.

Seasonal Variability

Figure A.5 plots the output of both the tracking and the fixed-tilt panels, averaged over a week for the 52 weeks of 2014. For both the tracking and fixed panels, the rate of production of solar power from all of the panels (in kilowatts) is divided by the total area of panels (in square meters). A tracking panel produces more power than a fixed panel in the spring and summer, but the two mountings perform approximately equally in the fall and winter. A tracking panel's output is about six times as large near the summer solstice (and also in one week in April) as near the winter solstice. Although tracking panels are more productive, adding tracking hardware

[29]Gokhale, Manali P, 2015. "An Analysis of Princeton University's Photovoltaic Field," Junior Paper, Spring 2015 (unpublished).

(including motors) adds costs. The trade-off is not clear cut. Indeed, utility-scale solar installations are being built today using both tracking and fixed-panel arrays.

The weekly data in Figure A.5 exhibit some bumpiness, rather than fitting a smooth curve. The bumps are rainy and cloudy weeks. Week-to-week variability, of course, is less predictable than the seasonal variation and nonetheless needs to be accommodated on the grid. In this instance, the costs of grid integration can be substantially reduced by good weather forecasting.

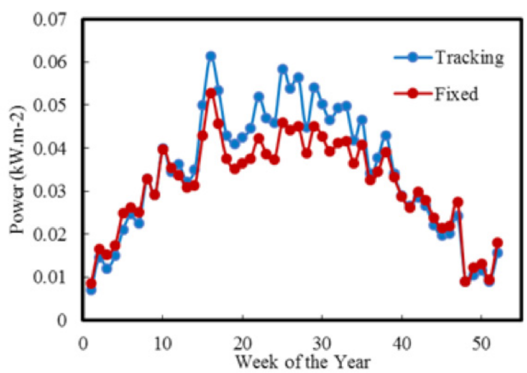

Figure A.5: Average weekly power production of tracking and fixed-tilt panel, divided by total panel surface area, for each week of 2014. Monthly averages were substituted for missing days of data.

Day-to-Day Variability

Figure A.6 shows, for the 365 days of 2014, hourly solar output from the tracking panels. The analogous record for the fixed-tilt panels looks similar, except for a difference in daily load shape that is discussed below. Looking at the entire year reveals intermittency on several different scales. Intermittency within the hours of the day is obvious; it is as predictable as sunrise and sunset. Day-to-day intermittency is much less predictable: a sunny day can be followed by a cloudy one during which hardly any power is produced. Note the four days in a row in the first week of January when almost no power was produced; weather data reveal that these were snowy days, and the panels may have been covered in snow. Deliberately, Figure A.6 does not display seasonal variability, because the peak value for each month has been made the same, 180 watts per square meter of panel area. This scaling enables the patterns in the winter and summer to be equally prominent. In fact, as seen above in Figure A.5, far more power is produced in the summer.

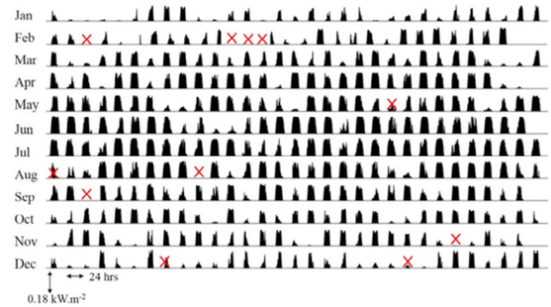

Figure A.6: Power production profiles for tracking panels in Princeton University's 5.4 megawatt solar installation for each day in 2014. Each month's peak hourly output is rescaled to be 180 watts per square meter of panel area. Red crosses indicate days when data are missing for at least part of the day.

Variability During the Day

The hourly profile for solar-panel output is at the heart of the challenge of integrating solar power into the grid, as the Duck Curve (Figure 5.1) makes clear. Detailed insight into these profiles can be obtained from the average hourly output of the identical panels equipped with two different kinds of mountings installed at the Princeton University project. Figure A.7 displays the average profiles for the fixed-tilt and tracking mountings on two specific sunny days (July 6 and December 26, 2014).

The most important feature is shared by both kinds of panels. As in the Duck Curve, the decline in output at the end of the afternoon is very steep – on both the winter and the summer days and for both tracking and fixed-tilt panels. On both days, however, the shape of the curve through the day is quite different for the tracking and fixed panels. On July 6 the output of the tracking panel power has a flat top, constant over much of the day. The Sun is high in the sky and high above the seesaw. By contrast, the fixed panel has a prominent peak at solar noon, when the Sun is highest in the sky, but the output drops off quickly on both sides of noon. Over the day, consistent with Figure A.5, the tracking panel collects more sunlight.

December 26th tells a different story. The fixed-tilt panels do better over the day than the tracking panels. The difference is most pronounced at noon, when the Sun is low in the southern sky, and the single-axis tracking panels are fully horizontal. The fixed panels, because they are tilted 25 degrees toward the south, see the noon Sun at a less oblique angle than the

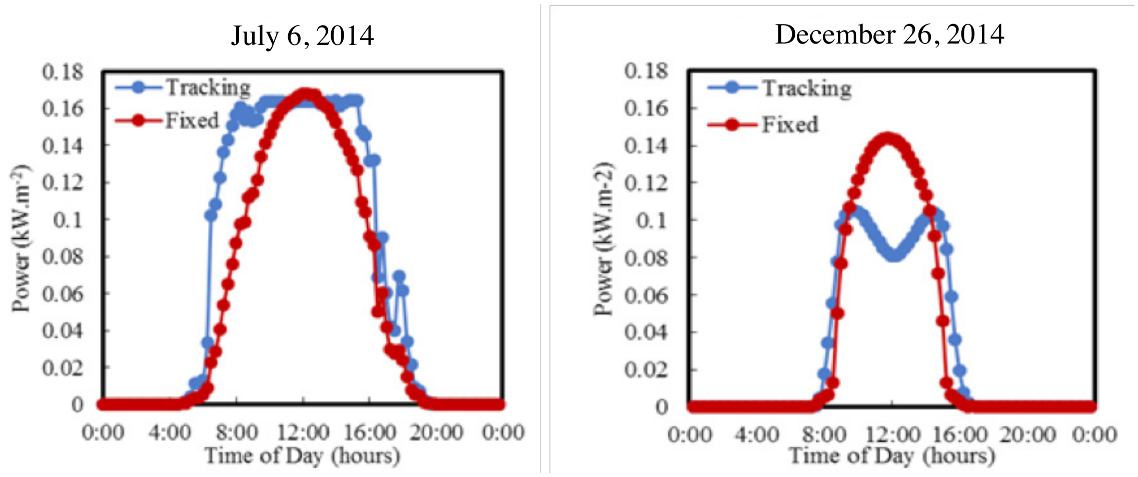

Figure A.7: Power production curves for tracking and fixed-tilt panels on July 6, 2014 (a sunny summer day, left panel) and December 26, 2014 (a sunny winter day, right panel). Power output (in kilowatts) is divided by the total surface area (in square meters) for each type of panel.

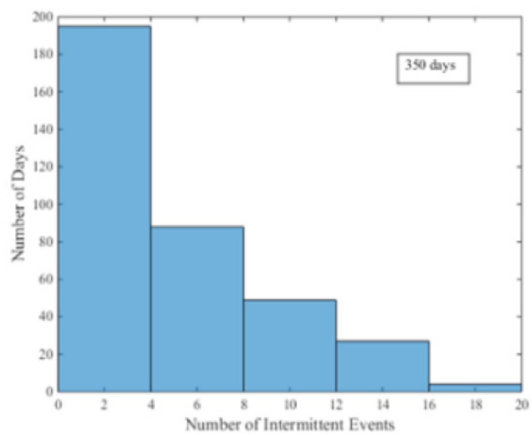

Figure A.8. Histogram of the number of days in 2014 with a certain number of rapid-change events, defined by output changing up or down by more the 30 watts per square meter of panel in 15 minutes. The first bin has zero to three events, the second has four to seven events, etc.

tracking panels and therefore produce more power. Note the "W" shape for the tracking-panel output: the tracking panels see the Sun better on both sides of noon than at noon, in mid-morning they look somewhat upward to the east, and at mid-afternoon somewhat upward to the west.

Variability in Minutes

Less amenable to help from weather forecasting than week-to-week or day-to-day variability are the rapid variations in solar input during partly cloudy days. Figure A.8 quantifies this form of variability by documenting the events during an entire year when power output from the solar field changed rapidly, up or down. Specifically, a rapid-change event was quantified as a change in power output of more than 30 watts per square meter of panel area in a span of 15 minutes – the time interval of our data. Because the maximum rate of production of electricity by the solar field is about 190 watts per square meter of panel area, what we are defining as a rapid change is a change of about 15 percent of the maximum possible change. Our analysis was restricted to the tracking panels. The number of such events per day, for 350 out of the 365 days in 2014 (the other 15 days had missing data), is plotted as a histogram with five bins. Nearly half of the days (roughly 160 days) have four or more rapid-change events. Many of these are the particularly troublesome partly cloudy days of the year.

Disposition of Princeton University's Solar Renewable Energy Credits

Princeton University earns New Jersey Solar Renewable Energy Certificates by operating its solar field. It currently sells these certificates to New Jersey's energy providers in a certificates market, enabling these providers to meet their mandated minimum production of solar power. However, the University is assessing the case for taking its certificates off the market in a few years and foregoing this revenue stream, in order to increase the amount of solar electricity produced in New Jersey. Those putting forth this argument assert that when the University participates in the certificate market, another potential producer of solar power will not do so, because the certificate market is designed to produce a specific amount of solar energy (its "solar carve-out"), not more. Selling its certificates, therefore, does not increase the amount of solar energy produced in New Jersey. Only when the University retires its credits rather than selling them, will other projects come into existence, with equivalent solar energy production, to meet New Jersey's mandated minimum requirement for solar purchases.

This argument assumes that the University's project by itself has no effect on the size of New Jersey's solar carve-out, and even its existence. The argument can be countered, however, if each New Jersey project, including the one at Princeton University, affects the overall level of interest in solar energy in New Jersey, and if that level of interest affects the targets set by the New Jersey's government. Targets are set many years ahead and will be revised only infrequently, but they can be revised upward or downward and can be challenged in state courts.