Model (At Least) Twice, Build Once: Experiences With the Design–Bid–Build Process for Solar Photovoltaic Arrays

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Commercial-scale solar photovoltaic (PV) arrays were designed, constructed, and are now operational on the Gaithersburg, Maryland campus of the National Institute of Standards and Technology (NIST). A design–bid–build process was followed where the contractors used photovoltaic system modeling tools both during the initial design phase and during the postbid, prebuild phase. To help investigate the specific aspects of the contractors’ evolving designs, the authors conducted their own independent photovoltaic system modeling. This independent modeling helped identify design elements that could be improved and so aided efforts to maximize the annual renewable energy generation. An estimated 2.5% gain in annual energy generation is being realized as a result of this independent modeling effort. To provide context for the modeling work and the lessons learned, key events impacting the design–bid–build process are described. The installed systems are summarized and also contrasted with the proposed designs. The power generation at three sites are compared over two different 12-month intervals. [DOI: 10.1115/1.4036055]

Keywords: photovoltaics, system, simulation

Introduction

The U.S. Government encourages its agencies to increase the use of renewable energy by implementing projects at federal sites [1]. The National Institute of Standards and Technology (NIST), an agency within the U.S. Department of Commerce, responded to this mandate by constructing photovoltaic (PV) arrays on its campus in Gaithersburg, MD. With a mission to advance measurement science, standards, and technology, NIST also saw the opportunity to use these installations to assist the photovoltaic community by providing a source of accurate field performance data. In advance of initiating the field monitoring effort, however, the authors conducted computer modeling to help evaluate some of the PV system designs put forward by the design and construction contractors. Design features that changed as a result of this independent modeling, as well as key features of the as-built installations, are described.

Detailed monitoring of three PV array installations on the NIST campus was initiated during the summer of 2014 [2]. The data collected from these systems is being used for multiple investigations. Examples of planned studies include: (1) comparing predicted with installed performance when using different PV system computer models and their varied input options; (2) evaluating different measurement and modeling approaches for day-ahead and day-of PV array power production forecasting; (3) documenting the impacts from shading, soiling, and snow coverage; and (4) quantifying the trade-offs from using progressively less detailed and less accurate field monitoring data for designing, maintaining, and troubleshooting a PV array.

The opportunity to conduct the monitoring effort came about, in part, as a result of providing technical assistance to the construction and maintenance department at NIST, which is here forward referred to as “NIST Facilities.” The authors accepted offers to attend meetings and review pertinent documents generated during the overall design–bid–build process of three larger and one smaller commercial-scale photovoltaic arrays. Observations made and a few related lessons learned from the opportunity to observe, offer comments, and minimally affect the process are shared.

The PV arrays went through a few design iterations during the prebid and prebuild stages. When given the opportunity to review an array design, the authors often chose to employ a commercially available computer program to model the electrical performance. Such modeled results provided NIST Facilities with an independent evaluation of the contractors’ own computer-modeled designs. Array tilt, spacing between module/row sheds, DC string layouts, the number of installed inverters, and the placement of other installed elements (e.g., fences, combiner boxes) are examples of the details evaluated by the authors. Ultimately, the independent modeling, coupled with a shared interest by the designers/contractors and NIST Facilities to implement reasonable changes, contributed to incremental improvements in the installed systems. Specific examples of this approach of modeling (at least) twice and building once are featured in this paper.

Design Process

NIST retained an architecture and engineering (A&E) firm to design multiple solar photovoltaic array systems for installation on its Gaithersburg, Maryland campus. Based in part from feedback provided by NIST Facilities, the A&E firm delivered drawings for erecting photovoltaic arrays at four different sites. The resulting drawings and related specifications constituted the key components of a procurement package that went out for bid. The winning bidder started construction in the spring of 2011; the four PV systems were made operational by August 2012. Limited monitoring of all four PV sites, as provided by the solar energy system subcontractor, was initiated at that time.

Pre-Award Stage. Prior to bringing in an A&E firm, NIST Facilities identified nine potential sites for new solar arrays. Factors that affected the selection of these initial sites included: (1) whether the site offered a relatively unobstructed view of the southern sky, (2) proximity to existing electrical mains, (3) impact on the esthetics of the campus, (4) a slight aversion toward installations on the campus’ several flat commercial building rooftops due, in part, to wanting to minimize future reroofing complications, and (5) excluding parts of the campus that contained trees, were near one of two ponds, or were areas that could potentially be used for erecting future buildings. For each of the initially proposed nine sites, the authors provided NIST Facilities with estimates of the average yearly solar insolation. These estimates were generated using a field-deployed instrument that quantifies local shading effects over an entire year based on a one-time measurement [3]. As per the instrument’s design, the field measurements were also converted into annual AC energy generation estimates using a commercially available modeling program [4].

NIST Facilities selected four sites using the above information, along with the knowledge of the available budget and a very rough estimate for the range of installed cost per array peak power output. These sites included (1) a portion of a parking lot, (2) a rectangular section of ground located immediately adjacent to a
campus research building, (3) a roof section adjacent to a rooftop array installed several years earlier, and (4) a small rooftop area on a separate NIST building. The parking lot option was selected while recognizing that its north–south-oriented parking rows (having east/west facing parking slots) would not be conducive to installing tilted, south-facing PV arrays.

The A&E firm developed proposed PV array designs for each of the four sites that, for the most part, offered symmetry and relative simplicity. Rather than explaining the bid designs here, key departures from the bid design are highlighted later.

The resulting bid package was structured to contain both required and alternate PV arrays. This strategy was taken in an effort to avoid having to rework and then repost the bid package if all the bids exceeded the allocated funding and to allow some flexibility in installing the amount of PV that best matched the fixed funding limit. The required elements amounted to a rated capacity of 441 kW by constructing PV arrays at three sites: the main portion of the parking lot design, all of the ground-mount design, and the smaller rooftop system. The three alternate elements collectively increased the rated capacity by 131 kW to yield an overall design total of 572 kW. These three alternates corresponded to the larger rooftop system and the option of adding one or two array shed canopies at the parking lot site.

All three of the alternate PV arrays, in addition to the required elements, were funded. The award was a single prime contract; a power purchase agreement was not pursued for this particular project.

Post-Award Stage. After the overall design package was released for bidding and the construction contract awarded, representatives from the winning contracting team met with NIST Facilities to discuss potential changes to the bid design, to solve complications not identified during the original design phase (e.g., avoiding interference with existing underground steam tunnels), and to address details not covered in the bid design. One of the key events of the overall design—bid–build process occurred at that time; the general contractor, at the recommendation of their solar energy system subcontractor, offered NIST Facilities three options:

1. Construct the arrays using the PV modules used as the basis for design in the bid package.
2. Use an alternative PV module having a higher rated efficiency to obtain the same rated system capacities specified in the bid package for each site. A slight overall savings was projected; this savings would be returned to NIST.
3. Use the same alternative PV module and maintain the same canopy, rack, and rooftop coverage as specified in the bid package. This option would increase the total installed capacity and require a corresponding payment increase from NIST.

After some consideration, NIST Facilities and the general contractor agreed to implement a fourth option: use the alternative model of PV module while reducing some support structures and the total number of PV modules installed but while increasing the installed rated capacity, all while having a net zero impact on the project’s total cost. The contractor’s efforts in identifying alternative modules, that otherwise met the bid specifications, benefitted both them and NIST.

The decision to go with a PV module other than the one used as the basis for design by the A&E firm, however, triggered a complete review and a substantial redesign of some PV system elements. As summarized in Table 1, although the two module options had similar footprints, their electrical characteristics were very different. The module that was ultimately installed not only had a higher rated efficiency (14.4% versus 13.4%) but, more importantly, had significantly different open circuit voltages and short circuit currents: 370 V and 8.60 A for the installed module versus 22.8 V and 12.11 A for the bid design module [5]. As a result of the higher module voltages, fewer modules could be connected within each series string (12 versus 24). The increased number of strings contributed to allocating more strings per combiner box and/or installing more combiner boxes.

### As-Built System Highlights

A total of 1152 modules are installed at the ground-mount array (Fig. 1), yielding a rated DC output of 271 kW. With the exception of the rear (most northern) shed, each of the five sheds is 48 modules across and five modules high, with the modules installed in a landscape orientation; the rear shed is four modules high. The distance between shed rows is 16 ft and the array tilt is 20 deg. As depicted in Fig. 1, a total of seven circuits feed the single inverter, which is located to the west of the five-shed array. Circuits SC1 to SC6 combine 14 series strings and circuit SC7 combines 12 series strings. Circuits SC2, SC5, and SC6 are created by combining series strings from two adjacent PV sheds. The other four circuits are created from strings contained entirely in one shed. To minimize the dominant shed-to-shed shading effect, as determined from modeling, east–west wiring of series strings were implemented. A cable-rail fence encircles the PV site and relatively long and narrow bio-retention ponds are installed along all but the west side of the array to minimize runoff.

At the parking lot site, a PV shed-style canopy was erected over each north–south parking row (that has east/west facing parking slots), as shown in Fig. 2. Within the lot’s interior parking area where two parking rows abut, two shed canopies also abut. To promote water shedding, each canopy is tilted 5 deg down from horizontal. As a result, four of eight shed canopies tilt to the west (Sheds #1, #2, #4, and #6) and the other four canopies tilt to the east. The modules are installed with their longer dimension running east–west. Each shed contains 129 modules laid out in a 3 (E-W) × 43 (N-S) grid. The rated DC power output at this site is 243 kW. Seven circuits feed the single inverter, which is located under the southern end of sheds #4 and #5. The number of series strings combined in parallel for each circuit is ten for circuits SC1 and SC7, 12 for SC5 and SC6, and 14 for the remaining three circuits. Circuit SC3 is distributed among Sheds #2, #3, #4, #5, #6, and #8; circuit SC6 is distributed among Sheds #1, #3, #5, #6, and #7. Circuits SC2, SC4, and SC5 contain series strings from abutting sheds. SC1 and SC7 are the only circuits created from strings contained entirely in one shed. Although burdensome to implement from a construction standpoint, all modules in a given series string have the same tilt direction in an effort to minimize mismatch within a string—i.e., the effects from differences in the plane-of-shade irradiances, west tilt versus east tilt. An ice shield is installed along the lower edge of each shed canopy.

The third installation, a larger ballasted PV rooftop array, has a rated power output of 73.3 kW DC. The 312 modules are distributed as shown in Fig. 3. Although not shown, module placements

### Table 1 Information about the solar photovoltaic module selected by the architecture and engineering firm versus the module installed by the general contractor

<table>
<thead>
<tr>
<th>Specifications (rated values)</th>
<th>Basis of design</th>
<th>As-built</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (W)</td>
<td>210</td>
<td>235</td>
</tr>
<tr>
<td>Open circuit voltage (V)</td>
<td>22.8</td>
<td>37.0</td>
</tr>
<tr>
<td>Short circuit current (A)</td>
<td>12.11</td>
<td>8.60</td>
</tr>
<tr>
<td>Maximum power voltage (V)</td>
<td>18.3</td>
<td>30.0</td>
</tr>
<tr>
<td>Maximum power current (A)</td>
<td>11.48</td>
<td>7.84</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>13.4</td>
<td>14.4</td>
</tr>
<tr>
<td>Module frame size (mm × mm)</td>
<td>1650 × 951</td>
<td>1640 × 994</td>
</tr>
<tr>
<td>Modules per series string</td>
<td>24</td>
<td>12</td>
</tr>
</tbody>
</table>

1Although not detected until after the original design was bid, the original design’s proposal to use 24 modules for each series string exceeded the NEC 600 volt maximum when worst case (i.e., coldest) operating conditions are considered.
avoid existing roof penetrations. Each individual ballasted rack mounts the module in a portrait orientation at a south-facing, fixed tilt of 10 deg. The horizontal spacing between each row of modules is 0.76 m (30 in). Four circuits feed the single indoor inverter. Circuit SC4 combines five series strings; each of the three other circuits combines seven series strings. As shown in Fig. 3, the series strings for circuits SC2 and SC4 are more spatially distributed than the comparatively unified SC1 and SC3 circuits.

The fourth installation, a smaller ballasted rooftop array, has a rated output of 8.5 kW DC. This 36-module array is installed using the same ballasted rack system as used for the larger rooftop system. Whereas the researchers have instrumented and are monitoring the performance of the three larger arrays, the performance of this smaller rooftop system is not being tracked except to the extent provided by the solar energy system subcontractor. Besides contributing PV generated power to the NIST grid, this small array provides replacement modules for any failures within the three larger campus arrays from the time that the manufacturer no longer offers an equivalent module until the arrays reach end of life (30+ yr). In such cases, the nonidentical, replacement module is deployed within the smaller rooftop array where footprint and electrical mismatch issues can be more readily handled and their negative effects best minimized.

Independent Modeling

Especially during the time that the construction team was reworking the A&E firm’s designs into a detailed set of construction drawings and specifications, the authors conducted independent evaluations of select PV array design elements. These and the other evaluations were facilitated by modeling the evolving designs using the PV array modeling tool PVsyst\(^2\) [6]. PVsyst is especially well suited because it includes a shading model—based on a computer aided drafting (CAD) model of the site—that can account for the effects of local shading on PV array production. Shade on even small parts of PV modules can significantly reduce

\(^{2}\) Certain commercial products or equipment are described in order to specify adequately the design procedure. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that it is necessarily the best available for the purpose.
Four examples of the findings and impact of the independent modeling process are provided below. The particular design elements selected are: (1) the placement of the fence at the ground mount array, (2) the series-string configuration at the ground mount array, (3) the ice guard installed at the canopy array, and (4) the module layout for the rooftop array. For all the modeling, the key output was the predicted annual energy production. More specifically, the relative change in this predicted quantity provided the means for comparing runs where only one or two variables were changed. The predicted loss in energy generation due solely to shading effects, as modeled by PVsyst, was also compared among competing designs to gain insight. The energy differentials and shading impact data aided NIST Facilities when deciding on what to “sign off on” versus what to ask the general contractor to further consider.

Ground-Mount Fence and Series String Configuration. As initially designed, the fence encircling the ground-mount array would have a height of 1.4 m (4 ft 7 in), with its south section being placed 0.9 m (3 ft) in front of the southernmost shed row of modules. The bioretention areas were to be placed immediately outside the fence on its north, south, and east runs. The independent modeling showed that the shading effects from the fence on the southernmost PV shed row would cause a 2.2 MWh/yr generation loss. Moreover, the modeling indicated that this loss could be almost completely avoided by increasing the separation distance between the south-side fence and this shed row from 0.9 m to 1.5 m (3–5 ft), or by increasing the ground clearance of the sheds from 0.6 m to 0.9 m (2–3 ft). As a result of this information, NIST Facilities and the general contractor implemented an as-built layout where the placement of the fence and bioretention area are reversed along the southern end of the ground-mount array, see Fig. 1. This decision eliminated any module shading from the fence but created a need to periodically trim any taller growing vegetation within the bioretention area (especially now that the fence hinders the natural trimming by the resident deer population).

The original design of the ground mount array called for connecting horizontally adjacent modules (i.e., east–west strings). However, following the decision to use an alternative module, the layout changed to having the modules connected in a serpentine manner, up and down the shed row (i.e., north–south strings). Independent modeling estimated a 1.9% increase in annual energy generation from using the east–west string layout when coupled with the above-described fencing change. As conveyed in the representative snapshot of Fig. 4, near shading is more impactful on the north–south string configuration for this site. After sharing this finding with the solar PV system subcontractor, they implemented the change, incorporated it in all subsequent design iterations, and ultimately constructed the array using horizontal strings.

Canopy Ice Guard. As conceived for the bid package, each parking lot solar canopy was to include a “continuous shield with 3 in minimum vertical.” This specification was included to limit chances that a sizeable section of snow or ice would slide off the canopy array and onto a car or pedestrian. The specific design for the ice shield was not covered in the A&E design drawings and, for the most part, not seriously considered until well into the construction phase. At that point, the construction team briefly discussed possible designs and then engaged a structural engineer to generate an implementable version. The resulting proposed design met the bid design requirement by adding a metal barrier that extends 20 cm (8 in) perpendicular from the 5 deg-inclined canopy truss, thus creating a 10 cm (4 in) shield when ice or snow accumulates on the PV modules. Upon learning of the inclusion of an ice shield and its initial design, the authors expressed their concern for generation loss due to the resulting shading. Using a PVsyst model, the proposed ice guard was found to decrease yearly generation by 11 MWh if the proposed shield was positioned 4 cm (1.5 in) from the framed edge of the PV modules in

PVsyst models were run for all of these shading and performance investigations. PVsyst version 5.21 was used with TMY3 data from Baltimore–Washington International Airport, which is 48 km (30 mi) from the NIST campus in Gaithersburg, MD. Component models of the as-built modules and inverters were used. Module layout and orientation, and shading from adjacent module rows and nearby objects were modeled using detailed CAD layouts of the sites and arrays, as created in PVsyst’s global scene building tool. Model inputs, such as wiring losses, module mismatch, and soiling were held constant at their default values. All models were run using a 1 h time step.

Specific elements that were investigated include:

1. the option of using two inverters at the parking lot canopies, one connected to the west-tilting modules and one connected to the east-tilting modules,
2. east–west (horizontal) versus north–south (serpentine) string configurations at the ground mount location,
3. row spacing and placement of the DC combiner boxes at the larger roof array installation,
4. tilt and height of shed rows and the spacing between them at the ground mount array,
5. the size and placement of the edge ice shields at the parking lot canopy, and
6. placement of the fence around the ground mount PV array.

or eliminate their power output and ultimately impact the power output of the series strings in which they reside [7–10].

Fig. 3 Larger rooftop array

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the lowest row, or 4 MWh/yr if placed 10 cm (4 in) away. A few additional combinations for the guard’s height and separation distance from the modules’ lower edge were modeled, with the results shown in Fig. 5. Agreement was soon reached on a revised design that maintained the specified safety functionality, caused negligible shading effects, and was constructed from stock material. As installed, the top of the guard reaches only 5.3 cm (2.1 in) above the top-of-module plane, as shown in Fig. 6, and is spaced 12.5 cm (4.9 in) from the modules’ lower framed edge.

Rooftop Array Layout. The original bid design failed to account for the need to space the tilted rooftop modules and did not address how to best work around the relatively few, yet impactful existing roof penetrations. In addressing the deficiency, the construction team proposed a layout that included a 61 cm (24 in) horizontal spacing between the 10 deg tilted module rows. Upon seeing this improvement in the initial set of construction drawings for the site, the authors checked for the time of the day when inter-row shading would begin on the winter solstice. The calculated time, 2:15 pm local solar time, was judged too early in the day to allow shading and so motivated the authors to model the rooftop system. The PVsyst model of the proposed array layout was first used to better understand the shading impact on the winter solstice (see Fig. 7). Next, the model projected the annual generation of the rooftop array to be 93.5 MWh. The authors asked the general contractor if the proposed roof rack hardware permitted creating a greater separation distance between successive rows without having to customize. In learning that the roof rack system hardware permitted a maximum spacing of 76 cm (30 in), the authors ran the revised PVsyst model using this slightly greater separation (while also confirming that no new conflicts with roof penetrations were created). The predicted annual generation increased modestly, by 1.1%.

Modeling Summary. The independent modeling helped the authors considerably by quantifying the impact of design elements that, at first pass, looked to be nonoptimized. With modeled numbers in hand, the authors could then approach NIST Facilities and the other members of the construction team to discuss the findings. At that point, changes could be considered (or quickly dismissed) based on how the proposed changes affected the construction schedule and budget. The authors estimate that the annual production of the installed systems was increased by 2.5% through the cumulative revisions implemented as a result of the independent modeling. This level of improvement translates into a substantial cost savings to NIST each year that could have easily been missed had the independent modeling not been conducted.

Designed Versus As-Built
A few notable changes that occurred between the bid design and the installed system are summarized in Table 2:
NIST gained an additional 23 kW of rated power production (at no additional cost).

The general contractor’s design reduced the total number of installed modules by 188 but, more importantly, reduced the size of the parking lot canopy by 10% and the number of rooftop racks by 5%.

Although not causing a reduction in the support structure, one complete row of 48 modules was eliminated from the ground-mount array (see Fig. 1, most northern shed row).

These changes are a direct consequence of the change to the as-built module. Other changes proposed by the contractor, and accepted by NIST Facilities, included a ground mount support system requiring considerably fewer concrete piers and reducing the width of the two book-end, shed-style canopies at the parking lot site.

As noted earlier, all of the installed PV arrays are created using series strings having 12 modules, compared to the A&E design of 24 modules per series string. As a result, the number of as-built series strings nearly doubled. The increased number of strings required more wiring, more interconnecting conduit, and ultimately more convoluted layouts. Trade-offs from using fewer combiner boxes but larger diameter cabling between the boxes and each site’s inverter were resolved during the prebuild stage after not being addressed during the design stage.

The installed electrical layouts depart from the symmetry and simplicity that may have been marginally oversold in the bid designs. For example, as compared to the as-built ground-mount system (Fig. 1), the original design included five equal-size sheds. Each shed contained the same number of series strings (10) that landed at a single, centrally located combiner box. The design layout of two east–west series strings per module row resulted in nearly identical overall wiring lengths.

For the parking lot canopy, the design called for each shed to contain the same number of series strings (6) that fed a dedicated combiner box. The designed system, with its eight equivalent DC circuits, thus differed greatly from the “make it work” as-built layout, as shown in Fig. 2.

An unfortunate compromise in this particular design–bid–build process is the layout of the as-built DC circuits (Figs. 1–3). Cleaner layouts would typically be proposed in an initial design. Resorting to more complicated wiring configuration should only occur if other design elements and budget constraints are already established and so greatly limit available options, as turned out to be the case for the NIST PV systems. Collectively, the selection of the as-built module, coupled with the practical factors of minimizing costs while staying as close as possible to the original PV array designs, lead to PV arrays that require substantive changes in order to create workable installed systems. On the surface, the as-built systems look much like the original designs. Upon closer review, however, creative wiring configurations were needed to do so.

### Installed Performance

A first read on the installed performance of the campus photovoltaic sites is gained by comparing the AC energy outputs. During the first 12-month period of operation, from August 2012 to July 2013, the four PV sites collectively generated 780 MWh.

This energy generation is equivalent to the amount of annual electrical energy needed to power 73 typical homes [11].

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**Table 2** Key differences between the bid design and the as-built systems

<table>
<thead>
<tr>
<th>Specification</th>
<th>Bid design</th>
<th>As-built systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total rated power (kW)</td>
<td>572</td>
<td>595</td>
</tr>
<tr>
<td>Total area of PV modules (m²)</td>
<td>4277</td>
<td>4148</td>
</tr>
<tr>
<td>Total number of PV modules</td>
<td>2724</td>
<td>2532</td>
</tr>
<tr>
<td>Total number of PV modules for each shed canopy</td>
<td>144</td>
<td>129</td>
</tr>
<tr>
<td>Total number of individual ballasted roof racks</td>
<td>372</td>
<td>352</td>
</tr>
<tr>
<td>Total number of concrete piers for ground mount array</td>
<td>280</td>
<td>170</td>
</tr>
<tr>
<td>Total number of canopy columns</td>
<td>50</td>
<td>45</td>
</tr>
</tbody>
</table>

*The number would have exactly doubled had the total number of modules not decreased slightly between the design and installation phases.*

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Fig. 7 Modeled results that pictorially and graphically show the impact of near shading for the worst case of the year, on the winter solstice, at the larger rooftop array for a module row spacing of 61 cm (Generated using PVsyst)
Although more of a fringe participant in the design–bid–build process, the authors found that independent modeling was beneficial for investigating design details proposed by the A&E firm and then by the solar PV system subcontractor. The modeled results provided quantitative information that aided NIST Facilities in deciding what to accept and what to challenge as the contractor’s site designs evolved. In most cases where a design detail was questioned, the contractor had either overlooked the detail or, at least, not given sufficient attention to its impact. Examples of system details that were changed as a result of the independent modeling include: (1) module row spacing for the rooftop arrays, (2) placement of the fence at the ground-mount site, (3) string configurations at the ground-mount, and (4) the size and placement of the ice guard for the parking lot canopy sheds. The authors estimate that the annual production was increased by 2.5% because of the changes that were implemented as a direct result of the independent modeling. In terms of the measured data, this modeling can be credited with contributing approximately 20 MWh every year to the annual energy production.

One lesson learned in participating in this design–bid–build process is that the purchaser of the PV arrays is better able to work with the (typically) more experienced contractor to get the best system possible if they have credible, independent modeling results. Such results help in finalizing details and avoid overlooked elements. In addition, such actions should further encourage the contractor to give the appropriate time and effort upfront so to avoid additional challenges, possible redesigns, and associated project delays.

Some other learned lessons pertain more to the general decision making and procedural steps of the design–bid–build process. For this NIST process, the decision to install a PV module that has significantly different electrical characteristics than the module used as the basis of design had the biggest impact. To avoid extra negotiations, substantial redesigns and the associated time delays, select a PV module for the basis of design that has a high probability of becoming the as-built module or is otherwise sufficiently representative of a subset of different best-candidate modules. For the latter, identify a set of cost-competitive candidates and then compare their key electrical characteristics—e.g., open circuit voltage, short circuit current, rated power—as well as their physical dimensions. Select a module that falls near the median in these categories.

Additional learned lessons include:

- For cases where the budget is fixed and a hard deadline exists for completing the bid phase of the overall process (as is usually the case for federal agencies like NIST), divide the bid package into required and alternate elements. The projected cost for the required elements must be comfortably below the available funding to avoid the need for reposting and possibly exceeding the deadline. The alternate elements should collectively increase the project’s overall cost to a level equal to or greater than the available funding. These alternate elements, in addition, should ideally be of different increments to allow flexibility in being able to get as much PV installed as possible. Such flexibility is especially helpful for cases where the price of PV modules trends up or down over the period between module selection for design and the receipt of bids.
- PV buyers need to be educated (and some designers need to be reminded) of the significant impact from even partial shading, especially if that shading effects multiple modules in different series strings rather than multiple modules in the same series string.
- Consider implementing a design that will offer an acceptable solution for the likely future scenario where one or more of the original modules fails and an exact replacement is no longer commercially sold. The small 8.5 kW array serves as the source for any module that must be replaced in the three larger arrays when the described failure scenario occurs.
- Exercise the general industry practice of not installing a rooftop system on a roof that is in other than very good structural condition. If the targeted roof location is not new.

Summary and Lessons Learned

Solar PV arrays at four sites on the campus of the National Institute of Standards and Technology were commissioned during the summer of 2012. Detailed monitoring at the three larger sites began in August 2014. The rated capacities of these four systems are 271 kW for a ground-mount system, 243 kW for a parking lot canopy system, and 73.3 kW and 8.5 kW for two rooftop systems. During their first 12 months of operation, the four arrays collectively generated 780 MWh.

To aid comparisons between arrays, their monthly and 12-month AC energy production totals are normalized by dividing each total by the array’s corresponding rated DC power output. Comparing just the three larger arrays, the 20 deg-tilted ground-mount system outperformed the 10 deg-tilted larger rooftop array and the 5 deg east- and west-tilted parking lot canopy by 4% and 12%, respectively, over the first 12 months of operation. The same comparison was then repeated using data collected 2 years later, from August 2014 to July 2015. This time the ground-mount system outperformed the two other arrays by the same percentage, 11%.

Fig. 8 Average daily specific yield for each month of the two reported periods (August 2012 to July 2013 and August 2014 to July 2015) for the three larger PV sites

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or in very good condition and a portion of the funding allocated for the PV system cannot be used to cover the cost of the reroofing, find another location to install the PV system.

- On a first cost basis, ballasted rooftop PV systems are more cost effective than systems requiring more support structure, as is the case for the ground-mount and the parking canopy systems installed at NIST. However, ground-mount and canopy structures have the potential for being re-used with a new set of PV modules when the current ones reach their end of life. The rooftop system, by comparison, will need to be completely removed and re-installed one or two times over that same 60+ yr period in order to allow reroofing.

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References


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