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16. ABSTRACT

Provide guidance to the California Department of Transportation (Caltrans) on the installation of utility-scale solar electrical generation facilities in its right-of-way. Explores the current rules, regulations, and policies from regulatory agencies external to Caltrans and California utilities that affect Caltrans' ability to install solar within its right-of-way. Determines best practices that other state departments of transportation have developed based on their experience with the deployment of solar generation facilities within their right-of-way. Outlines best practices of how to develop solar generation sites within Caltrans right-of-way. Summarizes design-build-own strategies that Caltrans could use as part of a public-private partnership to finance the installation and/or maintenance of solar sites within the Caltrans right-of-way.

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Solar Power Initiative Using Caltrans Right-of-Way — Final Research Report

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1 INTRODUCTION

The objective of this project was to provide guidance to the California Department of Transportation (Caltrans) on the installation of utility-scale solar electrical generation facilities in its right-of-way. Specifically, the project developed a written summary and a website that describe the current rules, regulations, and policies from regulatory agencies external to Caltrans and California utilities that affect Caltrans' ability to install utility-grade solar generation sites within its right-of-way. Additionally, the project determined best practices that other state departments of transportation (DOTs) have developed based on their experience with the deployment of utility-grade solar generation sites within their right-of-way. Third, the project documented best practices of how to install utility-grade solar generation sites within the Caltrans right-of-way. Last, the project explored and summarized design-build-own strategies that Caltrans could use as part of a public-private partnership to finance the installation and/or maintenance of utility-grade solar generation sites within the Caltrans right-of-way.

The work plan contained nine distinct tasks. The research team was led by Dr. Sarah Kurtz from the University of California, Merced, and was complemented by staff from the Texas A&M Transportation Institute (TTI) (Edgar Kraus, Kris Harbin, Dr. Cesar Quiroga, Dr. William Holik, and Brianne Glover), and KPMG Consultants (David Ross and Liam Kelly). To maximize project efficiencies, the research team conducted several tasks in parallel. Task 2 (conduct literature review) and Task 4 (develop website content) started immediately following the completion of the kick-off meeting. Task 5 (develop website) began after the kick-off meeting but required results from Task 4 to complete. Task 3 (conduct interviews) and Task 6 (explore design-build-own strategies) followed the completion of Task 2. Task 7 (determine installation best practices) was reviewed to confirm inclusion of information from the other tasks. The development of the draft and final research reports was facilitated by including the finalized reports from the other tasks without further review. The research team included a Division of Research, Innovation and System Information (DRISI) review period of approximately two months, which allowed the DRISI research oversight panel to review the draft research report and provide feedback.

Approach

1. Oversee Project Management
2. Conduct Literature Review
3. Conduct Follow-Up Interviews
4. Develop Content for Website
5. Develop Website
6. Explore Design-Build-Own Strategies
7. Determine Best Practices for Installation of Utility-Grade Solar Generation Sites
8. Complete Draft Research Report
9. Complete Final Research Report

The research team worked closely with the DRISI project manager and research oversight panel to ensure open dialogue and effective coordination. The research team included expertise in renewable energy and solar installations (Sarah Kurtz), procurement and public-private partnership mechanisms (David Ross and Liam Kelly), utility management on state right-of-way (Edgar Kraus), utility accommodation (Kris Harbin), utility engineering (Cesar Quiroga), and legal review (Brianne Glover).

2 DELIVERABLES SUMMARY

2.1 Literature Review Summary

The literature review summary (found in Appendix A: Literature Review Summary) provides a summary of the applicable literature related to department of transportation (DOT) practices deploying utility-grade solar generation sites within the right-of-way. The literature review included research reports, Caltrans documents, guidebooks from other DOTs, federal guidance documents, American Association of State Highway and Transportation Officials (AASHTO) references and surveys, and project reports resulting from the implementation of utility-grade solar generation sites. A separate effort reviewed rules, regulations, and policies concerning utility-grade solar generation, as summarized in Appendix C: Summary of Rules and Regulations, as well as the associated website.

The purpose of the literature review was to lay a foundation for the remainder of the project. The literature review is structured as follows:

- **Best Practices.** A summary of best practices identified by the research team and arranged by a variety of factors, including location and installation, maintenance, operations, safety, and environmental considerations.

- **DOT Solar Deployments.** A summary of solar deployments in the right-of-way by other state DOTs.

- **Planned DOT Solar Deployments.** A summary of solar deployments in the right-of-way that are currently being planned or implemented by other state DOTs.

- **DOT Solar Deployment Evaluations.** A summary of solar deployments in the right-of-way that are currently being evaluated by other state DOTs.

The literature review concludes with a discussion of the applicability of the main findings to Caltrans' ability to deploy utility-grade solar generation sites in the right-of-way. This summary captures the available literature in 2019. The solar industry is evolving rapidly, and the reader is encouraged to keep in mind the latest trends toward use of microgrids for resilience and inclusion of batteries for grid stabilization, which are not included in this review.

2.2 Follow-Up Interview Summary

The follow-up interview summary (found in Appendix B: Follow-Up Interview Summary) summarizes the interviews the research team conducted in the spring of 2020. The interviews were conducted with engineers who have implemented utility-scale solar facilities in their state right-of-way. The purpose of the interviews was to determine insight into best practices that were not available in the literature. To that end, the research team developed a questionnaire with 32 interview questions. Where feasible, researchers organized the information gathered from the interview process using the following structure of topics:

- **General Lessons Learned.** General recommendations and best practices that DOT staff offered during the interviews based on their experience with solar projects in the state right-of-way.

- **Project Development and Contracting.** Recommendations and best practices that DOT staff offered with regard to the development of solar projects and related contracting issues.

- **Electricity Generation and Storage.** Recommendations and best practices with regard to a solar project's electricity generation and storage, if applicable to the DOT's solar project.

- **Operation and Maintenance.** Recommendations and best practices with regard to operating and maintaining solar projects, including unexpected difficulties and costs.

- **Plans and Opportunities.** A brief summary of each state DOT's plans for solar projects in the right-of-way in the near future.

The research team targeted state DOT personnel from nine states: Colorado, Florida, Hawaii, Maryland, Massachusetts, New York, Ohio, Oregon, and Vermont. The research team was able to schedule interviews with seven states; Hawaii and New York were unable to participate. In many cases, project managers for the solar projects of interest were no longer with the DOT, so interviewed DOT staff were not always able to provide responses for all areas of interest described in the questionnaire.

Following is a summary of the lessons learned offered by the interviewees, arranged into four groups: solar program recommendations, which apply to a DOT's solar program that would develop and supervise many solar projects; planning phase recommendations, which apply to the early stage of solar project planning; development phase recommendations, which apply to the development of a specific solar project; and operations and maintenance recommendations, which apply to specific solar projects once installation of the solar project is complete. Please note that this is not a complete list of steps or considerations but rather a list of recommendations that DOT staff highlighted for each project phase:

- Solar Program Recommendations:
  - Assess the Solar Project Financial Viability.
  - Align DOT and State Administration Goals.
  - Consider the Definition of Solar Facilities as a Utility.
  - Formalize the Solar Program.
  - Consider Initial Project Effects on Solar Program Momentum.
- Solar Project Planning Phase Recommendations:
  - Estimate Solar Panel Maintenance Costs.

  - Evaluate Renewable Energy Incentive Programs.
  - Ensure a Diverse Solar Project Team Composition.
  - Consider the Combination of Solar Projects with Electric Vehicle Infrastructure.
- Solar Project Development Phase Recommendations:
  - Evaluate Contractual Options.
  - Consider Master Solar Contracts.
  - Define Clear Responsibilities.
  - Develop a Process for Solar Site Identification.
  - Evaluate Local Grid Interconnection.
  - Develop a Process for Public Involvement.
  - Evaluate the Expertise and Track Record of Solar Contractors.
  - Evaluate the Viability of Solar Equipment Companies.
- Solar Project Operations and Maintenance Recommendations:
  - Link the System Performance to the Operations and Maintenance Contract.
  - Have a Clear Plan for System Monitoring.

2.3 Summary of Rules and Regulations

The rules and regulations summary (found in Appendix C: Summary of Rules and Regulations) summarizes the numerous regulatory rules, regulations, and policies affecting Caltrans' ability to install utility-grade solar generation sites within the right-of-way. Regulatory agencies vary, from federal-level entities to California utility companies. The summary includes a detailed review of federal and state regulations as well as local utility companies' rules and policies concerning power purchase agreements (PPAs) and partnerships for the installation of utility-grade solar generation sites. In addition, the summary highlights current incentives available to Caltrans for the installation of utility-grade solar facilities in the right-of-way.

In 1988, the Federal Highway Administration (FHWA) revised Section 645.209 of the Code of Federal Regulations (CFR) to instruct state DOTs to follow AASHTO's *Policy on the Accommodation of Utilities within Freeway Right-of-Way* as before, or to adopt their own policies. This gave states the ability to implement their own policies, and today all states have utility accommodation rules (UARs) approved by FHWA.

In addition to the guiding principles provided by AASHTO, FHWA provides a list of provisions in 23 CFR 645.211 that should be included in each state's UARs. Updated in 2005, the

AASHTO policy states that DOTs have "various degrees of authority to regulate the use of utilities within highway rights-of-way generally through their authority to designate and to control the use made of right-of-way acquired for public highway purposes." The agency's authority depends not only on the federal law but also the individual laws and regulations of the state. To accommodate utilities in the state right-of-way, states must follow the procedures outlined in their UARs to evaluate and approve individual applications for utility facilities in their right-of-way.

Most states provide free access to public utilities on state right-of-way or right-of-way that is not access controlled. Many states do not allow longitudinal utility installations on controlled-access right-of-way or require compensation that might be defined in a lease agreement or shared resources agreement.

One of the most challenging concepts is the definition of when a facility is considered to be a utility. States typically define a public utility as any entity or corporation providing water, electricity, gas, telecommunications, or transportation to the public. Ownership does not necessarily have to be public, but the service must be for public use. There are some instances where a publicly owned utility can be regulated differently. A utility can be considered a private utility if it provides a service to a small number of customers or to private land as opposed to the general public. Depending on the definition used, there are different options to develop renewable energy facilities in the state right-of-way. Appendix C: Summary of Rules and Regulations discusses the current Caltrans definition, options for accommodating renewable energy facilities in the Caltrans right-of-way, and other potential options should this definition change in the future.

2.4 Website of Rules and Regulations

The research team developed a website with special emphasis to detailing current rules, regulations, and policies that affect Caltrans' ability to install utility-grade solar generation sites within the right-of-way. The website is hosted by Caltrans on the internal network (Intranet) that is accessible to Caltrans staff and authorized third parties at https://solar.onramp.dot.ca.gov/.

The research team worked with the Caltrans project manager to identify technical details for the website. The research team then developed the website layout and navigation details. Following the initial design and layout, the research team met with Caltrans several times to modify the website using an iterative process.

For example, as newly acquired information became available from the literature review, follow-up interviews, and legal review, researchers posted that information to the site. Website development resulted in the following main webpages:

- **Home.** The home page provides an introduction to the Solar in the Right-of-Way project, describing the three phases of the project and background information. It also provides a link to the various research project deliverables, meeting notes, and presentations.

- **Literature Review.** This page summarizes the efforts of the research team to document literature related to DOTs deploying utility-grade solar generation within the right-of-way and provides a link to the literature review report.

- **DOT Interviews.** This page summarizes results from interviews the research team conducted with seven state DOTs in 2020. The purpose of the interviews was to gather in-depth information about utility-grade solar projects in the right-of-way that was not available in the published literature.

- **Regulation Review.** This page summarizes the results of a review of laws and regulations pertaining to utility-grade solar projects at the federal, state, and local level.

- **Financial Summary.** This page provides a description and link to a document that explored design-build-own strategies that Caltrans could use with public-private partnerships to finance installation, operation, and maintenance of utility-grade solar projects.

- **Best Practices.** This page highlights the results of the best practices guide that discusses recommendations for streamlining the planning and installation of utility-grade solar generation sites within the right-of-way.

- **Final Report.** This page provides a summary and link to this final report.

- **Literature/Legal/Regulatory Reference Links.** This page provides links to all references included in the literature review and the review of rules and regulations, along with descriptions of the resources. A permanent PDF copy of this list of resources is stored on the Caltrans website.

- **Project Management.** This page provides information about Phase 1 of the research project, including the project manager information, contractors, proposal, research panel members, meeting presentations, and monthly reports.

- **About Us.** This page provides information about the Caltrans Technical Advisory Panel that provided guidance for the research team and reviewed the deliverables.

Some of these webpages provide links to several other webpages. For example, the page "Literature/Legal/Regulatory Reference Links" provides links to the following pages, each of which provides a listing of references with a brief description:

- **Research References.** References that were discovered and summarized in the literature review.

- **Federal Legal References.** References to federal laws, regulations, and policies that affect Caltrans' ability to install utility-grade solar generation sites in the Caltrans right-of-way.

- **California Legal References.** References to rules, regulations, and policies of California with regard to the installation of utility-scale solar facilities in the right-of-way. The references also include executive orders, senate bills, and assembly bills that pertain to solar installations.

- **Other States' Legal References.** Copies of other states' legal and regulatory references that pertain to the installation of solar projects, which may be of interest to Caltrans.

- **Utility Legal References.** Legal references from various California power utilities, including guidance on net metering, grid connections, and wholesale generator requirements.

- **Local Legal References.** References to guidance on the zoning and placement of solar facilities within city or county limits, which could be of interest to Caltrans if property outside of the state right-of-way would be needed to complete a solar project.

To help preserve web resources that might not be available in the future, researchers documented each web resource with the current link to the source and also created a PDF of the entire list of web resources, which is copied to the Caltrans server.

2.5 Financial Opportunities Assessment

The financial opportunities assessment (found in Appendix D: Financial Opportunities Assessment) is intended to provide commercial insights into various commercial structures, contractual relationships, and financing arrangements that might be utilized in the development, operation, and maintenance of commercial and utility-scale solar photovoltaic (PV) projects within Caltrans' right-of-way. These arrangements are also compared against more traditional PPAs with local power utilities. There are numerous commercial structure options that can be utilized with a third-party private partner involved to develop, deliver, finance, and operate solar PV projects. Depending on the requirements of Caltrans and the ownership interests of additional power off-takers and lessors, unique arrangements can be created to suit the needs of each participating party.

Before determining the best project development and delivery model for solar projects, it is critical for Caltrans to first evaluate the costs, initial capital, life cycle, and operations and maintenance for different models of power procurement. Each power supply model has varied benefits depending on the anticipated load, existing legislation, costs, generation locations, and transmission and distribution requirements. The assessment is broken into three major models of energy procurement and project delivery: self-ownership, public-private partnership (P3), and traditional PPA.

Examples of ownership and project development models include:

- **Self-Ownership.** Caltrans would self-fund and own a solar project, issuing contracts as needed for design, build, and operations and maintenance support.

- **Third-Party PPA (P3).** Caltrans would enter a contractual arrangement with a private entity to design, build, finance, operate, and maintain (or any combination thereof) a solar project, with little to no upfront capital investment required by Caltrans.

- **Solar Lease / License Revenue (P3).** Caltrans would lease unused land within the right-of-way to a private developer, who would develop a solar project and make set land lease payments to Caltrans.
- **Morris Model (P3).** In this hybrid PPA and bond issuance model, a private developer would design, build, operate, and maintain (or any combination thereof) a project, with Caltrans and the Department of Treasury providing low-rate financing.
- **Utility Contract (Traditional PPA).** Caltrans would have a standard PPA contract with a local utility with set rates and terms.
- **Direct Access (Traditional PPA).** Caltrans would establish a PPA with an electricity service provider as opposed to a utility, potentially offering lower power pricing.
- **Regional Renewables Choice (Traditional PPA).** Caltrans would establish a PPA with a choice of the supply stream but remain connected to the local utility.
- **Community Choice Aggregation (Traditional PPA).** Caltrans would establish a PPA in which power is procured from an alternative supplier, while transmission and distribution services are provided by the local utility.

Examples of funding and financing approaches include:

- **Appropriated Funds.** Funding directly appropriated to Caltrans.
- **Financing against Caltrans and State of California Funds.** Funding outside that which is appropriated to Caltrans, including the State Highway Account, Senate Bill 1 (Rebuilding California), and others.
- **Climate Resilience Bond.** Proposed financing measure in the governor's 2021 budget.
- **Climate Catalyst Fund.** Proposed financing measure in the governor's 2021 budget.
- **Cap-and-Trade Funds.** Funding through the California Air Resources Board earmarked to reduce emissions from transportation, among other items.
- **Lease Revenue Bonds.** Bonds structured around a loan made to the state that is repaid by income generated by an infrastructure project.
- **Private Capital.** A private enterprise providing equity or debt financing.
- **Project Revenues.** Monies received from a land lease agreement or sale of electricity.

2.6 Best Practices Summary

The best practices summary (found in Appendix E: Best Practices Summary) is designed to facilitate efforts by Caltrans to utilize the right-of-way for solar projects. It is intended to be used by Caltrans engineers who are already experienced with construction projects but have little experience with solar energy and solar systems. The summary reviews the parts of a solar system, how the design of the system can best take advantage of the available solar resource, how to select a site for a solar deployment, how to ensure success at each stage of construction of solar systems, and how to maintain the solar systems over their decades of operation. Two case studies are analyzed to facilitate understanding of the material.

The summary assumes that Caltrans will work directly with solar contractors who will be familiar with local code requirements and who have already demonstrated successful deployment of solar systems.

The focus of the summary is on knowledgably managing solar contractors rather than on becoming solar contractors. While Caltrans may be large enough to eventually develop an internal capability to execute solar projects, there are two reasons why it is a best practice for an organization like Caltrans to contract with a solar installer: (a) economics, and (b) the learning curve.

1. *Mass production is more economical*: The dramatic reduction in solar prices is largely a result of economies of scale: solar installers have been able to streamline the installation process by gaining experience with a specific set of hardware (and consistent system design), reducing the time and effort needed for designing a system, decreasing the number of parts that need to be stocked, and facilitating rapid installation. As an example, companies installing utility-scale systems have designed a block that installs 1 MW. Whether a customer wants a 1-MW plant, a 100-MW plant, or something in between, the design in every case is built from 1-MW blocks, resulting in very minimal design cost for each new system.

2. *The learning curve is steep*: As highlighted in the interviews with other DOTs (e.g., the interview with the Florida Department of Transportation) and as experienced by the wider community in the last three decades, putting together a solar system is a straightforward project that can be done by most any engineer, but putting together a solar system that will not have issues is not straightforward. The reasons for failures can be wide ranging, including using a combination of metals that corrode (as was the case in Florida); installing cables that blow in the breeze or expand and contract in a conduit and become abraded, sometimes leading to a fire or ground-fault interrupts; replacing the module clamp with a different clamp because the first one is not available, resulting in module breakage; and finding that the local ant population loves the taste of a material in a junction box. Some design errors are caught quickly. Others may take years to be identified and resolved. Thus, working with an installer who has already climbed the learning curve in California can circumvent severe headaches later on.

Some key best practices highlighted in the summary are the following:

- **Size the system for local load**: At a rest area or a maintenance yard, a system sized to meet the local load ensures a customer for the electricity.

- **Ensure adequate delivery of electricity to the load**: If the system is designed to generate more electricity than can be used locally, analysis will be needed to ensure that the local distribution lines and/or transmission lines are adequate to deliver the electricity to the load.

- **Add storage**: As a surplus of solar electricity on sunny days becomes more common, it will be increasingly advantageous to include batteries to be able to use the solar electricity after the sun sets.

- **Shift loads**: Similarly, if loads can be shifted to times when the sun is shining, the solar electricity will be most valuable for the application.

- **Remember that larger systems often provide lower cost**: If the goal is to supply low-cost solar electricity, it might be preferable to participate in a large solar installation that is optimally sited rather than attempting to install a solar system that is close to the load but in an awkward location.

- **Utilize local code knowledge**: Caltrans will benefit from working directly with solar installation contractors who are familiar with local code requirements and who have already demonstrated successful deployment of solar systems.

- **Promote standardization**: While local code requirements must be followed, Caltrans may choose to support the industry's efforts to move toward harmonization of local standards with international standards.

The summary includes solar-specific information for managing construction projects, but not for the design and construction itself since the construction should be done by a company that specializes in solar system construction. Some of the details provided may help guide decisions about site selection or contractor selection, but most are focused on operations and maintenance since that aspect can be handled in house.

3 PROJECT EVALUATION

This section summarizes successes and challenges pertaining to each task as perceived by the research team. Overall, tasks were developed and completed as planned, and most deliverables were submitted on time. Some of the tasks changed slightly in scope, which resulted in an adjustment of the work schedule acceptable to both Caltrans and the research team. Despite the challenges with the COVID-19 pandemic, Caltrans provided excellent project oversight. The project manager was always actively involved, provided feedback when needed, and was readily available to answer project-related questions. The research team appreciated Caltrans' offer to extend the final project deliverable due date at no cost to the project.

3.1 Project Management

The project schedule proposed by the research team provided start and end dates for each task. With the exception of Task 8, which involved completing the draft report, the proposed schedule did not provide for a review period by DRISI following the submission of each task deliverable, or a period for review and update of the draft deliverable by the research team immediately following the DRISI review. The intention of the research team was to incorporate comments and finalize each deliverable while completing the draft research report. Caltrans requested, and the research team agreed with, a different approach that would finalize each deliverable once the research team received comments from Caltrans. This approach did not change the scope or duration of the project but shifted some of the work from later in the project to an earlier time. This change also resulted in a shift of project durations since task durations then included a DRISI review and deliverable update period.

3.2 Literature Review Summary

The literature review started on time and was completed on time with no delays. The research team submitted the draft deliverable on November 27, 2019, as planned. The research team received comments on January 21, 2020, and submitted the final deliverable on February 17, 2020.

3.3 Follow-Up Interview Summary

This task started on November 28, 2019, which was on time, but the due date of February 12, 2020, was delayed for several reasons. The researchers received approval of the list of questions to use in the interviews on December 28, 2019. The researchers started contacting the target DOTs the first week of January but found it difficult to schedule meetings with all appropriate officials. The Caltrans project manager helped set up two meetings, the last of which was conducted in the middle of March 2020. Researchers continued to attempt to conduct the final two interviews, but with the onset of the COVID-19 pandemic, the research team ceased this effort at the end of April.

The research team generated draft notes from the meetings and submitted the notes for comment to the DOT staff interviewed. This effort took significantly more time than anticipated. COVID-19 most likely impacted this effort, both on the research team's side and on the side of the state DOT staff interviewed. Once the unedited draft was completed, the schedule for editing by TTI editors had also shifted, resulting in further delays. As a result, this follow-up interview task (Task 3) and Task 7, development of the best practices guide, did not occur in sequence but to a large degree in parallel. The Task 3 deliverable was submitted to Caltrans on August 28, 2020.

In hindsight, the research team was too optimistic in its ability to schedule the interviews and develop the report on time. The COVID-19 pandemic impacted the research team's ability to schedule interviews, receive timely feedback, develop the draft report, and submit the edited deliverable.

3.4 Summary of Rules and Regulations

The rules and regulations summary went overall as planned. The draft task deliverable was submitted to Caltrans on December 13, 2019, nine days after the planned due date of December 4. The delay was due to information that the researchers became aware of in early December and wanted to include in the draft deliverable. The researchers received comments on March 27, 2020, and submitted the final deliverable on July 27, 2020.

3.5 Website of Rules and Regulations

The task to develop the website of rules and regulations went differently than planned. The original plan was to develop a website layout in parallel with Task 4 (summary of rules and regulations) and then complete the website shortly after Task 4 was complete. However, Caltrans' preference was to use an internal content management system, which simplified website development considerably. Caltrans then asked the research team to incorporate the findings and sample data collected during Task 3 (follow-up interviews) into the website. As a result, the task due date was pushed toward the end of the research project, and the task became an ongoing activity that involved continuous updates to the website. The research team agreed with all requested changes to the project task, and changes did not create any issues for the research team.

3.6 Financial Opportunities Assessment

KPMG leveraged its extensive experience on this topic to provide a summary at minimal cost. There was some delay in initiating this effort, but once David Ross was brought on board, KPMG was actively engaged and even available for in-person conversations.

Financial approaches to funding solar projects are constantly changing, especially depending on changing policy. Continued engagement with KPMG or another firm that is actively executing solar financing contracts may be useful in the future.

3.7 Best Practices Summary

The best practices summary was the largest of the deliverables, so this effort took substantial time to assemble. Input from Caltrans to define the desired case studies was very helpful.

The schedule would have been improved by building in time for an external review. The addition of the external review was welcomed by everyone, but it delayed submission of the summary. Photographs and graphics demonstrating primary points were found to enhance the readability and clarity of the summary.

3.8 Final Research Report

The development of this final research report required less effort than originally planned. The original plan was to incorporate comments received on the draft task deliverables in a large final report deliverable; however, Caltrans requested that the research team attach finalized task deliverables as appendices to a relatively short final report. This change allowed the research team to catch up with the project due dates and submit the draft of the final research report on time on September 3, 2020.

4 THE FUTURE OF SOLAR

The solar industry has grown impressively in the last decades, especially as the price of solar modules dropped by more than a factor of 10. Figure 4.1 shows the global electricity generation, illustrating the rapid relative growth of solar and wind in recent years. This rapid growth has reached a critical time in that, although the electricity generation by renewable technologies is still a small fraction (Figure 4.2, left), it has become a large fraction of newly installed capacity (Figure 4.2, right). The rapid growth shown in Figure 4.1 is now slowing since solar and wind already dominate new deployments. Increased electricity demand (e.g., from electrification) will be needed to continue the rapid growth of solar deployments.

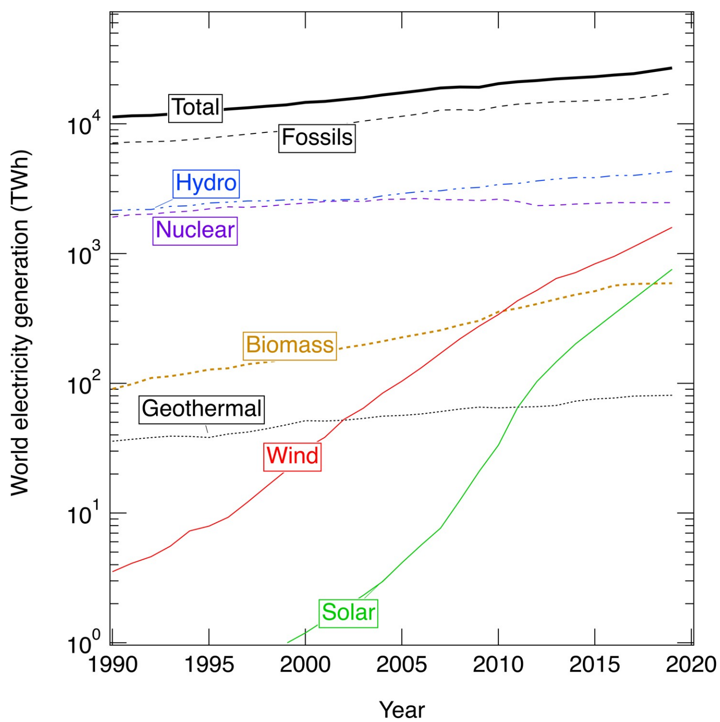

Figure 4.1. Annual world electricity generation as a function of year for major technologies.
Data source: Energy Information Administration (EIA).

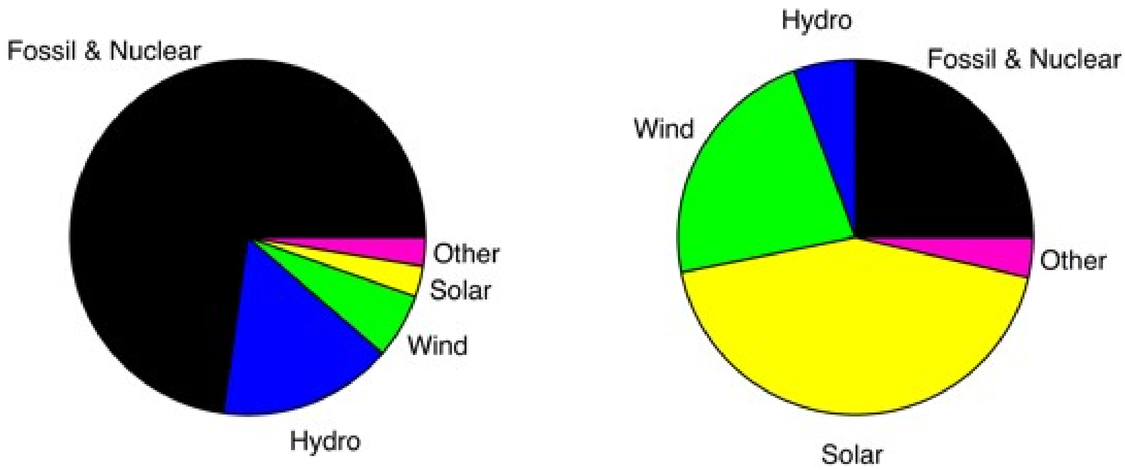

Figure 4.2. For 2019, global electricity supplied as a function of technology (left) and global net capacity expansions for electricity generation as a function of technology (right). Data source: REN21.

California has been a leader in the growth of solar electricity, as shown in Figure 4.3, which reached 20 percent of California-generated electricity in 2019.

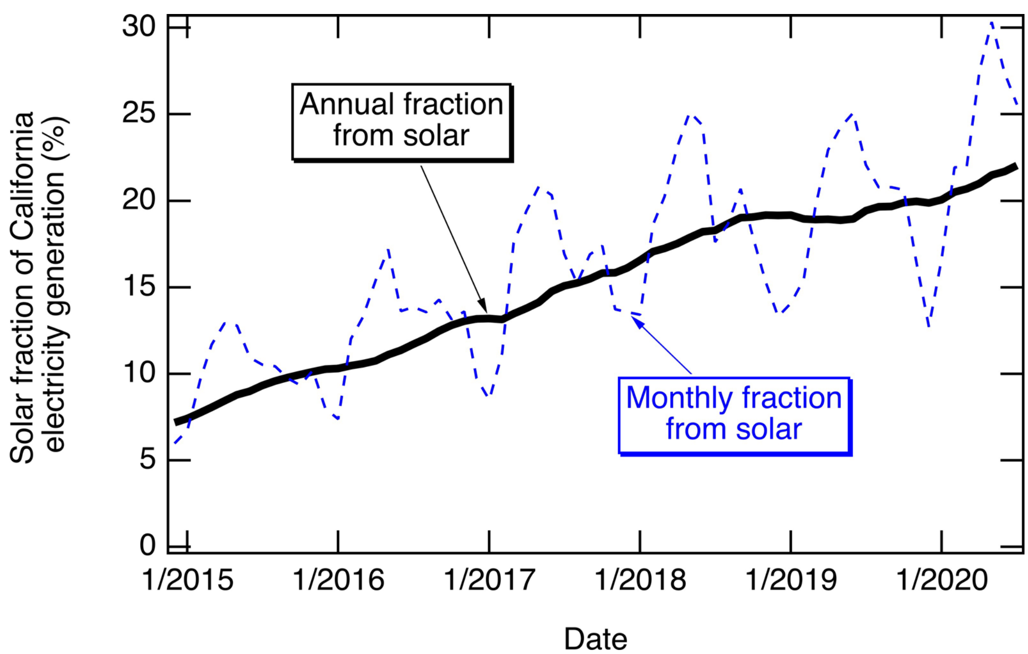

Figure 4.3. Fraction of electricity generated by solar each year within the state of California. Data source: EIA.

4.1 Solar Panel Technology

Solar panel technology has and will continue to evolve quickly. Some of the topics that will become increasingly important are discussed below.

4.1.1 Manufacturing

Solar cell and solar panel manufacturing moved to China, much like the manufacturing of many other products. There has been much discussion in both the United States and Europe about bringing the manufacturing back. The momentum toward local manufacturing may be accelerated by the pandemic and how it has identified the risk of relying on a global supply chain. However, even if the manufacturing capacity in the United States were to double, it would still be only a small percent of the total world capacity. Furthermore, China has been expanding its manufacturing capability and appears to be recovering from the pandemic more quickly than the United States, suggesting that moving manufacturing back to the United States may not become a large trend.

4.1.2 Solar Cell Technology

Silicon solar cells have dominated the market, with a market share greater than 80 percent throughout the industry's history and a current market share of over 95 percent. The second-place technology is cadmium telluride, with sales dominated by First Solar, the largest U.S. solar panel manufacturer.

The silicon market is shifting rapidly from multicrystalline to monocrystalline silicon. The most recently developed process is a hybrid of the two and may be called *seed casting*[1] or *directional solidification*. The process starts with one or multiple wafers as the "seeds" for the crystal growth, which then quickly enables crystallization in the direction orthogonal to the original wafers. The quality of the crystal is close to the quality of a monocrystalline wafer, while the cost is close to that of multicrystalline silicon.

Traditional aluminum back-surface field silicon cells are rapidly being replaced by designs with higher efficiency, including some that can be made in bifacial format. Bifacial modules are rapidly gaining market share, especially for applications that make use of light on the back of the module.

In addition to the changes in the types of wafers being used, the sizes of the wafers are increasing,[2] contributing to the increased panel size, as described next.

4.1.3 Solar Panel Size

In the last year, new modules with a rating of more than 500 W have been making headlines, with more and more companies joining the "500W+" club. However, at SNEC 2020 (the largest

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[1] See, for example, https://www.youtube.com/watch?v=EZQtJU0Ib9Q.

[2] See, for example, https://www.pv-magazine.com/2020/10/22/update-of-the-itrpv-roadmap-shows-three-wafer-formats-will-prevail/.

trade show globally) in August 2020, even larger products were introduced, with the largest topping 800 W.[3] The trend toward larger power ratings is enabled by higher efficiencies, bifacial designs, shingled cells, half-cut cells, and/or larger cell sizes. The highest wattages also require panels of larger size. Some of these are definitely here to stay. Higher efficiencies are now being achieved without significant increase in cost by using PERC cells or one of several other cell architectures that can reach higher efficiency. Bifacial designs can make use of light striking the back of the panel, so they are especially useful when substantial light is able to strike the panel backsides. Shingled cells (see Figure 4.4) make the cell-to-cell connection by placing the edge of one cell on top of the edge of the adjacent cell, eliminating the needed space between the two cells and thus enabling higher efficiency at the panel level. There have been substantial reliability concerns with shingled cells, but some companies are gaining confidence in the ability of the shingled assembly to provide long lifetimes. Larger cell sizes reduce the number of parts that need to be assembled in a module but also increase the current, which is proportional to the area of the cell. Recently, the technology for controllably cutting the cells in half (or even smaller for the shingling) enables fabrication of large cells that can then be assembled into low-current, high-voltage modules, reducing series resistance losses and enabling larger modules.

[3] See, for example, https://www.pv-tech.org/editors-blog/snec-2020-how-modules-topping-800w-and-new-bipv-innovations-stole-show.

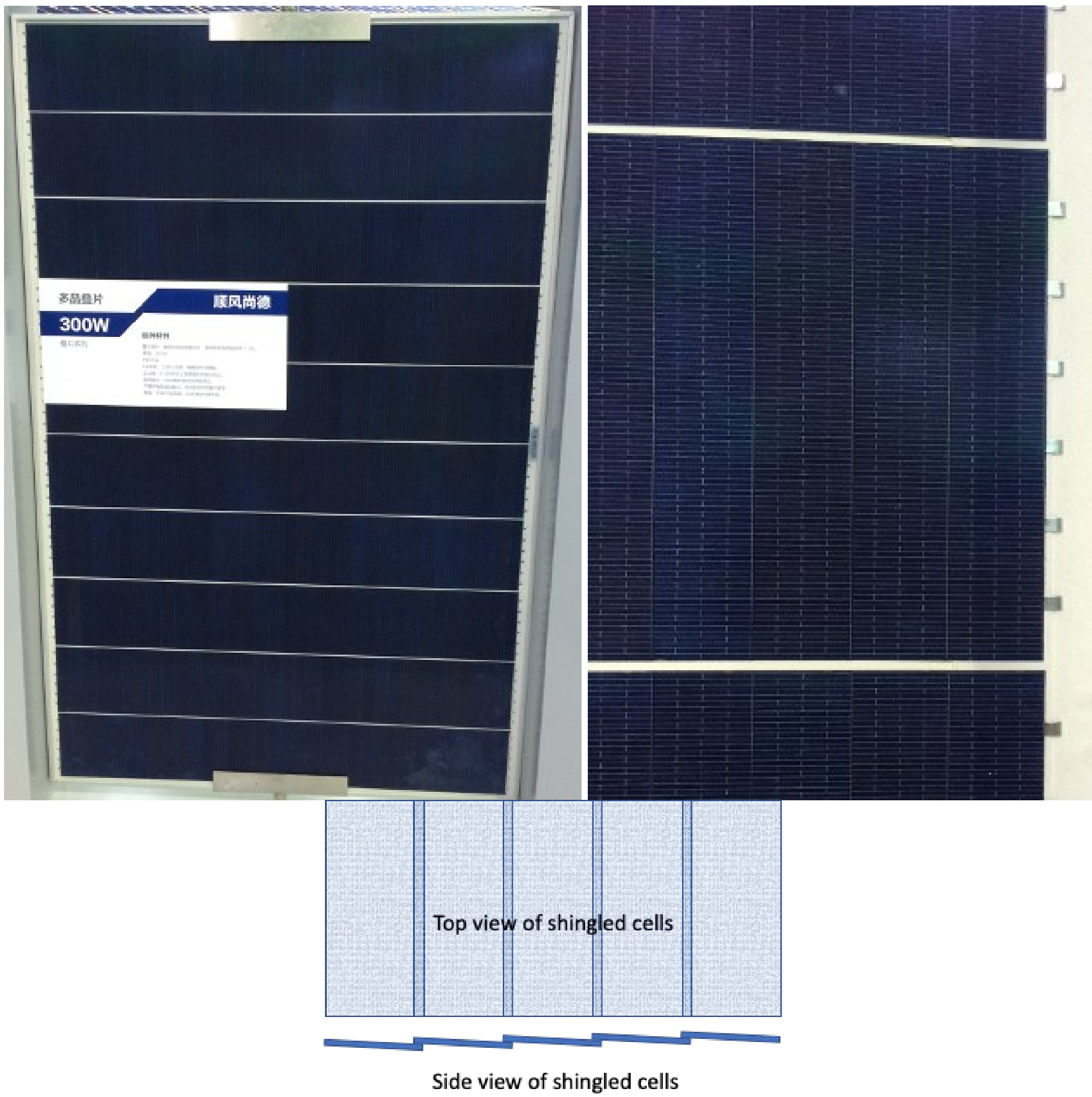

Figure 4.4. Shingled-cell module. Top left shows photograph of module made with shingled cells. Top right shows a close-up image of one row of cells. Bottom shows a schematic of how the cells are assembled so that there is no space between them. Note that there is still space between the rows of cells, as seen by the horizontal lines in the photographs. Photo credit: Sarah Kurtz.

The large-wattage modules are being demonstrated, and 600-W to 650-W modules are now commercially available. Whether they gain market share is yet to be seen. The primary barriers are the potential need for either two people or a crane to handle the large-sized module and the added reliability issues associated with the larger size. The large-wattage modules are mentioned here as examples of the many ways solar technology is evolving. An experienced contractor will begin to sample new technologies to gain experience before installing large numbers of a new product.

4.2 Solar System and Grid Integration Technology

Arguably the most important development in solar systems is related to the addition of storage. California's August 2020 rolling blackouts occurred at a time when a heat wave increased demand across much of the western part of the United States, reducing the available electricity for import. As the sun set, the available electricity generating capability was inadequate to ensure stable operation of the grid, and rolling blackouts were used to decrease demand on an emergency basis. While additional solar plants are needed to meet California's goals, that solar must be accompanied by storage that can ensure adequate supplies even as the sun sets.

As hybrid plants, which combine solar with batteries or with wind and batteries, are becoming more common, the designs of the solar systems will increasingly consider how the system can support grid reliability. The ratio of the power rating of the modules (direct circuit [DC] rating) to the power rating of the inverters (alternating circuit [AC] rating) has been increasing but may increase substantially more if low-cost storage can be identified. A DC-AC ratio of 2 or even higher may become optimal to enable enough charging of the storage during the day to deliver electricity well into the night.

The design of a system with solar plus batteries is not yet well defined. Considerations include what type of battery to use, what type of charge controller to use, and how to make the system safe.[4]

Storage technologies are rapidly evolving. Not only are battery technologies evolving, but new storage technologies are becoming available that may be routinely used for a few days of storage, including off-river (closed-loop) pumped hydro, gravity (using large blocks), flow batteries, liquid air, thermal, and geomechanical[5] storage. These are all exciting options, but the developments that may be of most interest to Caltrans are related to electricity and transportation.

An obvious synergy for Caltrans is to have solar panels that can be used to charge electric vehicles (EVs). EV owners are likely to be willing to pay more for parking when they will be able to recharge their batteries. Many people park at park-and-rides during hours when solar electricity is being generated, making it an obvious match. At the same time, fuel-cell vehicles may find it useful to be able to recharge at rest stops and elsewhere with green hydrogen (e.g., hydrogen made from solar electricity). Japan has targeted use of hydrogen to be a cornerstone of its future energy system.[6] Honda has been developing solar-powered hydrogen-generating systems that can refuel fuel-cell vehicles.[7] The speed with which fuel-cell vehicles will be adopted is somewhat controversial. However, there is general agreement that fuel cells are already well established for powering forklifts. Using solar power to generate the hydrogen would make a lot of sense since that would decrease the need to bring in a large transmission

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[4] See https://www.greentechmedia.com/articles/read/aps-battery-fire-explosion-safety-lithium-mcmicken-fluence.

[5] See https://www.pv-magazine.com/2020/08/19/a-battery-chemistry-schism-is-imminent/.

[6] See https://www.s-ge.com/en/article/global-opportunities/20201-c5-japan-hydrogen-market.

[7] See https://asia.nikkei.com/Business/Honda-to-install-faster-filling-hydrogen-stations-across-Japan.

line for the amount of electricity needed to generate the hydrogen. As the cost of electrolyzers drops, interest is increasing in pairing solar systems with electrolyzers for hydrogen generation, as in a 50-MW plant recently announced in the Netherlands.[8]

Many studies suggest that transmission lines provide one of the lowest-cost options to keep the grid stable. In the extreme, one can imagine connecting the grids in different parts of the world, connecting across the north pole so that China could send electricity to the United States when it is nighttime in the United States and the United States could send electricity to China when it is nighttime in China. Similarly, transmission lines could connect the southern and northern hemispheres. However, building transmission lines is difficult because of the need to identify a corridor, and local groups typically object to providing access through their backyards. Further, states have been objecting to transmission line corridors unless there is a direct benefit to the state. While installing transmission lines along highways[9] could reduce political hurdles to installing new transmission capability, the width of the right-of-way is not typically adequate for above-ground lines, and buried transmission lines are expensive (though they typically reduce fire risk so may be preferred in some situations). The use of the right-of-way for transmission or distribution is likely to continue to be controversial, just as the expansion of the grid elsewhere will be controversial.

Finally, Caltrans may find that solar panels installed on electric trains or along the tracks could provide convenient power for trains. If batteries were included in the train, the solar could charge the batteries during the day and the train could use the stored electricity to run at night.

4.3 Growth of Solar in the Right-of-Way

As solar is becoming ubiquitous, other states are discussing deployment of solar in the right-of-way. A recent report by the University of Texas at Austin[10] estimates that such systems could generate up to 36 TWh per year and provide about $4 billion in economic value to the state DOTs. Specifically, for California, the report suggests that there could be about 1800 GWh/y, with an estimated value of $330 M/y. The report has assumed ($330 M/y)/(1800 GWh/y) or $0.18/kWh. This is a retail rate, so it apparently assumes that the systems are installed to supply a local load using net metering. The delivery of 1800 GWh/y will require approximately 1 GW of installed systems. If $1/W installation cost is assumed, the upfront installation cost would be about $1 billion, suggesting a return on investment in about 3 years, which is excellent. However, using the median prices shown in Figure 4.5, and assuming that systems may be around 100 kW, one may anticipate prices closer to $2.50/W or $3.50/W, with anticipated payback time closer to 10 years. On the other hand, if the system is located where there is no nearby load with the plan to sell electricity on the wholesale market, the revenue will be

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[8] See https://www.pv-magazine.com/2020/10/21/baywa-r-e-and-alliander-develop-solar-plus-hydrogen-in-northern-netherlands/.

[9] See https://pv-magazine-usa.com/2020/08/10/ferc-advises-congress-how-transmission-may-be-co-located-with-transportation-corridors/.

[10] The Ray Solar Highway Project: Assessment of solar potential installed in ROWs across the United States," by E.A. Beagle, K.J. Richardson, J.D. Rhodes, and M.E. Webber. https://19fgew3zyb632ma8181lw82b-wpengine.netdna-ssl.com/wp-content/uploads/2020/09/Solar_Interstates_Ray_Report_FINAL_Aug2020.pdf.

substantially lower. If no storage is included, the electricity will be sold during the day, when prices are relatively low. If prices averaged $0.03/kWh, then the revenues would drop and the realistic payback time could be increased to about 50 years. The potential for a system to provide a payback time ranging from 3 years to 50 years emphasizes the importance of identifying what will happen to the electricity and whether the system can be built at record low prices (because of a large-sized system and minimal cost for site prep, permitting, and planning) or at prices closer to median values, as shown in Figure 4.5.

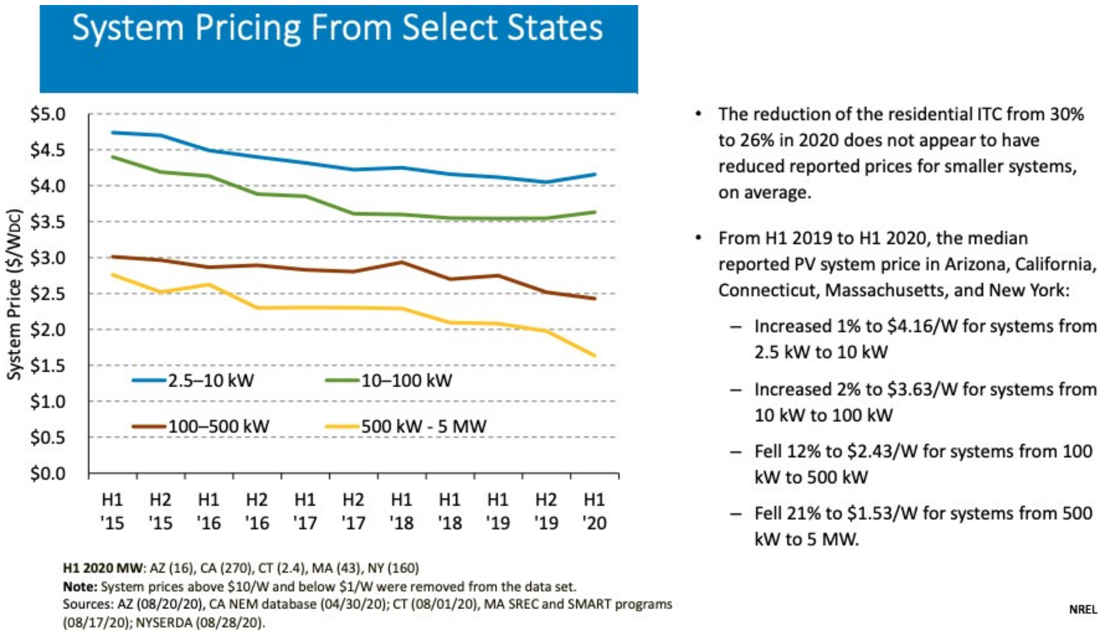

Figure 4.5. Recent solar pricing data.[11]

4.4 Business Model Evolution

One of the biggest barriers to investment in renewable energy is that most of the funds are needed at the beginning. In comparison, natural gas plants are relatively inexpensive to build but require purchase of natural gas throughout the life of the system. Thus, building renewable energy requires mobilization of significant amounts of capital. Fortunately, in today's world, capital is available and interest rates are quite low. Finding ways to attract that capital into investment in solar systems will be critical to growth of the solar industry.

As the world seeks ways to recover from the COVID-19-induced recession, it is probable that funds will be allocated for infrastructure investment. Although it is not yet known the form these funds will take, there will likely be opportunities for solar projects financed in a variety of ways.

[11] https://www.nrel.gov/docs/fy20osti/77772.pdf.

APPENDIX A: LITERATURE REVIEW SUMMARY

Caltrans Project No. P1253
Caltrans Task No. 3177

Solar Power Initiative Using Caltrans Right-of-Way—Literature Review Summary

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Submitted to

DIVISION OF RESEARCH, INNOVATION, AND SYSTEM INFORMATION
CALIFORNIA DEPARTMENT OF TRANSPORTATION

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INTRODUCTION

This document provides a summary of the applicable literature related to department of transportation (DOT) practices deploying utility-grade solar generation sites within the right-of-way. The literature review included research reports, California Department of Transportation (Caltrans) documents, guidebooks from other DOTs, federal guidance documents, American Association of State Transportation Officials (AASHTO) references and surveys, and project reports resulting from the implementation of utility-grade solar generation sites. A separate effort as part of the Task 4 deliverable (Develop Content for Website of Current Rules, Regulations, and Policies) has reviewed rules, regulations, and policies concerning utility-grade solar generation.

The purpose of the literature review is to lay a foundation for the remainder of the project, which includes conducting interviews with select agencies, developing content for the webpage, determining best practices on how to install utility-grade solar generation sites within the state right-of-way, and exploring the design-build-own-maintain strategies other states have used. The literature review will be included as a chapter in the final report that will be submitted at the conclusion of the project. The literature review is structured as follows:

- **Best Practices.** A summary of best practices identified by the research team and arranged by a variety of factors, including location and installation, maintenance, operations, safety, and environmental considerations.

- **DOT Solar Deployments.** A summary of solar deployments in the right-of-way by other state DOTs.

- **Planned DOT Solar Deployments.** A summary of solar deployments in the right-of-way that are currently being planned or implemented by other state DOTs.

- **DOT Solar Deployment Evaluations.** A summary of solar deployments in the right-of-way that are currently being evaluated by other state DOTs.

The literature concludes with a discussion of the applicability of the main findings to Caltrans' ability to deploy utility-grade solar generation sites in the right-of-way. This summary captures the available literature in 2019. The solar industry is evolving rapidly, and the reader is encouraged to keep in mind the latest trends toward use of microgrids for resilience and inclusion of batteries for grid stabilization.

BEST PRACTICES

This section describes the best practices for implementing solar projects that the research team identified using available literature. The research team will use the information included in this section to identify topics for interviews with stakeholders, which are intended to provide additional details about best practices and further enhance the best practices presented in the final report.

DOT Policy

A best practice when implementing solar right-of-way projects is for DOTs to take the initiative and provide leadership (*1*, *2*, *3*). The DOT's utility accommodation policy can be a valuable resource in this process since it might have a great effect on the state's ability to implement solar projects in the right-of-way. DOTs whose utility accommodation policy does not currently include solar installations will benefit from revising their policy. Unless precluded by statutory law, research recommends updating the utility accommodation policy to include solar installations in the state's definition of a utility and include design requirements for installations to facilitate solar project implementations (*1*, *2*, *3*, *4*, *5*). Both New Mexico DOT and Virginia DOT reported that implementing solar projects in the right-of-way becomes easier, and may not need Federal Highway Administration (FHWA) approval, once the utility accommodation policy includes solar installations (*6*, *7*).

Solar implementations at DOTs may be driven by cost reduction and/or greenhouse gas reduction (*7*). Some state DOTs actively pursue the reduction of greenhouse gases and recognize that solar energy can play a role in this effort (*1*, *2*). The effort to reduce greenhouse gases may be motivated by internal sustainability programs or state directives and mandates (*7*). Most DOT solar programs are backed by state mandates to reduce greenhouse gas emissions and increase renewable energy (*7*). Solar energy development is consistent with national and state DOT priorities since it helps contribute to lowering greenhouse gas emissions (*2*, *8*). Caltrans is committed to supporting sustainable clean technology, reducing air pollution, and improve reliability of the electric grid (*9*).

General Project Considerations

This section summarizes best practices for the location and installation of utility-grade solar equipment in the right-of-way, including considerations related to project selection, long-range transportation plans, preliminary screening, and environmental considerations.

Project Selection

Project selection involves the determination of the scale and features of a right-of-way solar project and plays an important part in the project's success and creation of value to the DOT and the public. Benefits of a successful solar project might include increasing energy security, offsetting DOT operating costs, adding value to the right-of-way, mitigating greenhouse gas production, and creating jobs that contribute to preserving or restoring environmental quality (*1*, *10*, *11*).

DOTs have an obligation to the public to make responsible choices in investing resources, and determining the solar installation project's economic feasibility should be part of the process (*12*). Conducting a financial analysis will help in determining the economic feasibility of the project. Some of the areas to consider when performing a financial analysis are system information, operation and maintenance, and financing and taxes (*6*).

Project information should include financial data on the development, equipment, and grid connection costs (*6*). Operation and maintenance information should include the annual costs for operations and maintenance, escalation rate, and decommissioning funding (*6*). Financing and taxes should include items such as the tax rate, grants and incentives, credits, net present value, loan rates, depreciation, and electricity costs (*6*). Assumptions that might be related to the system's electricity, including the output, cost of produced versus grid electricity, and cost escalators, can have a large impact on the financial analysis (*6*). Other variables that will have an impact are the life of the system, change in public policy toward solar projects, and net present value (*6*). Having a set economic analysis will help the DOT make more informed decisions regarding moving forward with solar installation projects (*12*).

The project selection approach varies depending on project specifics and other factors. As a DOT becomes more experienced at selecting and implementing solar projects, a model selection process and project specifics might be established (*1*). When starting a new solar in the right-of-way program, there are benefits to a DOT remaining flexible to changes in the selection process and to encouraging DOT staff and stakeholders to be creative in overcoming obstacles to installing solar projects in the right-of-way (*1*).

Long-Range Transportation Plans

A transportation improvement program is a multiyear capital improvement program of transportation projects. Each metropolitan planning area develops a transportation improvement program that is then incorporated into the statewide transportation improvement program. Transportation agencies also develop long-range transportation plans that outline the vision for the region or state's transportation system and services. In metropolitan areas, the long-range transportation plan indicates all the transportation improvements scheduled for funding over the next 20 years.

Long-range transportation plans should be considered when developing solar projects to identify site conflicts. Renewable energy projects can also be incorporated into long-range planning efforts. Typical lease agreements are for 20 to 25 years, which fit within the long-range transportation planning horizon. DOTs should consider these plans when determining the feasibility of solar projects (*1*).

DOTs have an interest in ensuring that no competing highway uses of land used for solar projects exist, especially during the early years when tax benefits are subject to recapture. Solar project agreements likely will include provisions for removing projects, restoring the site, and returning the land to the DOT, including reasonable compensation for early termination. The compensation needed to make developers whole is much less after the tax benefits and significant project development costs have been recovered (*12*). Some researchers recommend flexibility in contract language in case road configurations change in the future (*7*).

Preliminary Screening

The preliminary screening process is used to narrow down the potential sites for the installation of solar projects. The screening process is usually performed when there are many potential sites to choose from (*12*). If sufficient right-of-way data is available to narrow down potential solar installation sites effectively, all available right-of-way is usually included in the preliminary screening. If the right-of-way data is insufficient or not in a useable format, another strategy is to concentrate on sites within a specific geographic area or utility service area (*6*, *12*). The preliminary screening should include site considerations such as safety, solar energy potential, grid access, competing uses, site access, land requirements, natural features, and adjacent community activities (*6*, *12*). Google Earth can be used to help identify potential sites, as was seen during the screening performed by Sacramento Municipal Utility District for a proposed Caltrans solar project in the right-of-way (*2*).

The screening process should not be performed without involving stakeholders. The screening process is an opportunity for internal as well as external stakeholders to be involved since they can provide assistance in focusing the list of potential sites (*6*). Field personnel in local DOT maintenance offices can provide information about potential sites and can provide additional insight (*6*). Once sites have been initially selected, it is important to work with the DOT highway engineers to ensure the sites do not conflict with relevant AASHTO guidelines (*12*).

The screening process should look for sites with a good southern exposure based on the assumption that solar panels will be installed facing south. This procedure will allow the panels to maximize their electrical generation potential by capturing more sunlight (*2*, *6*). Sites can also be condensed by omitting areas that are impacted by shading, which may include vegetation on adjacent property, buildings, and topographic changes (*6*). Another consideration regarding shading is to find sites that minimize the potential for the solar installation to shade the roadway and clear zone. This element is particularly important for highways that experience icy conditions since the shade from the solar installation may prevent ice from melting as fast as it will in surrounding areas (*6*). The DOT can also use the estimated amount of solar radiation a site receives in the preliminary screening analysis. The National Renewable Energy Laboratory has solar resource information and data available through its website (*6*, *13*, *14*).

The screening should also include an assessment of current as well as planned uses of the right-of-way, including changes in highway alignment (*6*, *12*). This assessment should include any competing interest in the use of the right-of-way (*12*). Part of the report for the Vermont Agency of Transportation's solar plan included interviews with stakeholders and DOTs. One output of the interviews identified that most people prefer maintaining scenic views rather than installing solar equipment (*6*). This finding does not mean that every solar installation will block scenic views; some areas of the right-of-way may not have any views that would be impacted. Some of the natural views to consider include major natural features like lakes and vistas (*6*).

Environmental Considerations

Preliminary Environmental Screening

A preliminary environmental screening should follow the DOT's policies and procedures. Any recommendations in this section are intended to enhance or supplement the DOT's current procedures. An initial step in a preliminary environmental screening should be a review of readily available information related to the project (*12*). For projects in the right-of-way, this review may include research completed for the environmental process of other projects in which a solar site location was included. This review should focus on the changes or impacts of the solar installation at the new location (*12*).

Environmental resources, such as water (including wetlands) and endangered and threatened species, should be preliminarily identified (*6*, *12*). These sites should be considered for removal due to the potential impact the project may have on environmental resources. The DOT should be able to reach out to the appropriate division and the state's natural resource agency for assistance in identifying areas where the project may impact the environmental resources (*6*). Another important item to consider is if the portion of the right-of-way was affected by Land and Water Conservation Act funds because this may impact the use of the site (*6*). The review should also determine if the site selection will have an effect on wildlife refuges and recreation areas (*6*). The preliminary screening should further include archaeological and historical considerations. At the screening stage, the DOT should consider whether to pass on sites that may include more complex public involvement and environmental reviews; however, a final conclusion regarding their usage may be postponed pending further investigation (*6*, *12*).

Increased noise from construction of the solar installation may be a concern for the surrounding areas (*12*). Depending on the location of the solar installation in the right-of-way and its proximity to certain areas, the noise level may be a real or perceived issue. Restricting construction work to certain times of the day and limiting work on the weekends may resolve or lessen the impact from noise during construction. Long-term activities that may impact the noise level include vegetation removal and the reflection of sound off the panels (*12*). Performing a noise study may help lessen the public's concern and should be included as part of the site evaluation process.

Potential project sites that are known or thought to have major impacts will probably require a more detailed environmental review (*6, 12*). The additional environmental reviews will take time and add cost to the site development. For a site with significant environmental impacts, the added time and cost might make it nonviable for the installation (*7, 12*). A best practice is to concentrate on sites that look like they will have little impact or will be considered a categorical exclusion in the environmental process (*12*). In addition, the DOT's preliminary screening should address anticipated issues related to changes as a result of the solar installation: local land use, geology, historical and cultural resources, scenic views, socioeconomics, hazardous materials, water resources, and biodiversity (*2, 12*).

Electromagnetic Fields

The effects from electromagnetic fields (EMFs) can be a concern to the public. These concerns led Oregon DOT to contact the U.S. Department of Energy for information (*15*). This process, in turn, led the National Renewable Energy Laboratory (NREL) to perform a literature review on the health effects of EMFs (*15*, *16*, *17*). The NREL report found that the amount of exposure to an EMF at the perimeter of solar installations is lower than many household appliances (*2*, *15*, *16*, *17*). Oregon DOT also performed its own review of potential EMF effects of its solar installations. The review found that the levels from the solar installation are not greater than background levels and are not a public health concern (2, *18*).

Even though past studies have shown that EMF exposure to the public from solar installations should not be a concern, it may be a good practice to perform an EMF study if there is concern that the public might be apprehensive about EMFs for proposed installations. Concern may also exist about the combined effects of EMFs due to the growing installation of microcell towers and 5G cellular antennas in and near the right-of-way.

Aesthetics
Many DOTs install their initial solar energy generation projects in locations that are highly visible to the public. This effort can help raise awareness of sustainable energy efforts and the associated benefits. Many DOTs choose interchanges for solar energy installations because they have vacant land outside of the clear zone that is highly visible to motorists on multiple highways (*2*).

It is important to consider how the solar installation will impact the existing site features from the viewer's perspective (*6*). If possible, the solar installation should fit in with the surroundings to minimize distractions to the traveling public (*2*). Even though the installation itself should be a minimal distraction, this does not mean that the project cannot be visible. Ideally, the solar installation should be seen as an asset for the surrounding community (*2*).

For example, many solar panels along the right-of-way may be perceived as an eyesore. Working closely with local municipalities and the public can help address aesthetic impacts and develop mitigation strategies. If a large amount of negative feedback is heard from the public, it may be best to place solar sites away from neighborhoods (*7*).

For the proposed solar in the right-of-way project at Caltrans, Sacramento Municipal Utility District worked with an architect to develop renderings of the installation (*2*). Sacramento Municipal Utility District also planned to engage the surrounding community in selecting the final design (*2*), which is a great way to help gain support for an installation that will be a fixture in a community for a long time. It is also a good idea to require the developer to remove graffiti and keep the landscape of the installation maintained (*2*). Certain types of vegetation that create a visual buffer may help with the aesthetics of the installation (*6*).

Responsibility for Environmental Analysis
The responsibility of performing various parts of the environmental study may vary depending on project specifics (*2*). It is important to keep in mind whose responsibility it is to perform certain parts of the study. In Massachusetts, it was the developer's responsibility to comply with environmental regulations, whereas for the Oregon solar in the right-of-way project, it was the DOT's responsibility to ensure environmental compliance (*2*).

Stakeholder Involvement and Project Buy-In

Solar projects in the right-of-way involve many stakeholders, both internal and external to the DOT. Communication between stakeholders is very important to the success of the project. Keeping a consistent message regarding the solar project is equally important so everyone involved knows the status of the project on certain issues and can help minimize the need to reassess the same issues (*2*). Projects should have an outreach plan that includes target audiences and stakeholders, project description and need, outreach tactics and activities, and mechanisms for gathering feedback and addressing concerns. Potential project stakeholders include (*12*):

- Adjacent property owners and neighbors.
- Impacted transportation system users.

- Local officials and decision makers.
- Internal agency staff.
- Energy providers.
- Regional and local jurisdictional partners.
- Local businesses.
- Community civic organizations.
- Environmental interest groups.

The sections below provide a detailed discussion of project stakeholders and public involvement activities that should be included when developing solar projects in the right-of-way.

Stakeholder Partnerships

To successfully implement solar generation projects, DOTs should work collaboratively with utility companies, public utility boards, banks, private energy developers, and alternative energy vendors. These relationships will be valuable assets in educating DOT staff and resolving issues later in project development. Partnerships with utility companies and public utility boards allow for sharing data and maps on subsurface utility facilities to avoid utility conflicts when installing solar projects (*2*).

Agency Involvement

On federal-aid right-of-way, FHWA must be included in the project development process. It is beneficial to have solar sites preselected when meeting with FHWA to discuss potential solar projects and to help gain FHWA buy-in on a project (*7*). For example, New York State DOT's solar plan prescreened 50 potential sites, which affirmed to FHWA that New York DOT was serious about its strategy and approach to implementing solar projects (*7*). Anticipating and addressing any concerns FHWA may have early in the process provides additional benefits. New York DOT prepared an information packet—designed to lay out and address FHWA and federal requirements and concerns—for use during discussions with FHWA officials (*6*).

Support from state administration is important for a right-of-way solar project. State support makes DOT buy-in easier and helps get projects implemented (*6*, *7*). Some state support may be linked to state priority issues or mandates, such as addressing climate change or reducing greenhouse gas emissions (*7*, *9*, *19*).

Having the support of the DOT is necessary for the successful implementation of a solar project (*2*). For example, FHWA noted during state DOT peer exchanges that many participants mentioned the importance of having buy-in from DOT leadership (*20*, *21*).

FHWA also highlighted the importance of buy-in from DOT staff: involving local DOT offices in the site selection process is important to create local buy-in and support for a solar project (*20*). Staff buy-in is important for a successful project since local staff are usually responsible for project implementation. It may help to demonstrate how the project aligns with the DOT's mission and state administration goals (*7*). In fact, project managers at state DOTs and toll authorities find it important to have a defined project goal and purpose and to show management support (*7*). FHWA notes that support from all levels of DOT administration, including leadership, departments, and districts, are important for project success (*2*).

Some states include developers and other potential partners in the site selection process; however, states have reported mixed outcomes to this approach (*20*). It may be attractive to potential partners to have an initial site selection step completed prior to their involvement (*12*). In one case, a state DOT issued a request for information (RFI) about solar development within the right-of-way but did not generate interest from developers. An inquiry found that developers were not interested because the request required developers to commit a lot of time, effort, and expenses to conduct due diligence screening of sites (*7*). More positive outcomes were reported when potential sites were included in the official request. A possible option is to include potential sites but also give developers the opportunity to recommend additional sites (*7*).

Public Involvement

A well-crafted public involvement and communication strategy reaches out to stakeholders, informs and gathers input from project stakeholders, and promotes the project to the public. Public support for solar projects in the right-of-way is a decisive factor in the success of these projects. Several DOTs have held public outreach meetings, develop visualizations, and gather feedback about proposed projects. DOTs also continue public involvement efforts after project implementation, including providing real-time information about the amount of electricity produced by solar installations (*2*, *12*). DOTs should rely upon their public involvement and public relations specialists to assist with the public involvement phase of project development.

Communication Strategies

Solar installations are usually visible projects that will get the attention of the public. It is important to be prepared to receive and address the public's questions and concerns. Researchers recommend that DOTs create a website to provide project information, including the reason for the project and progress updates (*12*, *22*). There may also be interest in tours of the solar installation and site. Site tours should only be conducted if the safety of the tour group as well as the traveling public is not impacted (*12*). As an alternative to a live tour, a virtual site tour can be included on the solar installation's project website or at DOT kiosks located inside DOT buildings or at a location near the project site (*12*). If the DOT decides to allow tours, policy and plan documents should be prepared to assist in handling tour requests (*12*).

The public may have concerns about solar installations located near them. For example, individual landowners may show a special concern when the installation is adjacent to their property (22). It is important to make a public outreach effort early in the project to communicate the project to adjacent landowners (*22*). This outreach will help address any concerns early on in the process and hopefully resolve any objections to the project (*22*).

Outreach Activities

Public outreach should be performed to notify the public of planned solar projects. Typically, these projects are well publicized. DOTs can create public involvement and communication plans for solar projects that include planned outreach actions. Types of outreach include unilateral, bilateral, and multiparty communications. Unilateral tactics are useful for reaching a broad audience with minimal effort and include websites, press releases, and direct mail. Bilateral tactics such as one-on-one meetings and phone calls are more time consuming and costly but generate more candid exchanges. Multiparty tactics include community meetings and online forums that can reach broad audiences and help with project transparency. However, these approaches can devolve into an opportunity for critics to vent frustration and reduce the opportunities to share project benefits. The most effective multiparty tactics encourage small group interactions, such as open houses or project site tours (*12*).

Public Feedback

In addition to outreach, gathering feedback from the public is important in developing solar projects. Because these sites are highly visible and intended to be viewed as community assets, DOTs should involve the community in evaluating proposed project designs. Solar projects should blend with the highway and surrounding natural environment as much as possible to maintain a continuity of visual form (*2*). The public outreach campaigns should include a process to gather and respond to feedback from the public. This process is similar to that used for many transportation projects.

Project Champion

Solar installations are unusual projects compared to projects that DOTs handle on a daily basis, so it can be expected that issues will come up during the project (*2*). When issues surface, a project champion can help guide the project, alleviate stakeholder concerns, and create buy-in.

Several reports state that a dedicated project champion is essential to the success of a solar project (*2*, *3*, *23*). For example, Oregon DOT noted that its solar project was successful in large part due to a project champion (*6*, *7*). To be efficient, the project champion should be in an upper-level management position, as was the case for Oregon's first highway solar project (*7*). The project champion is expected to help coordinate stakeholders throughout the process but still needs a group of dedicated and skilled project members to support the champion's efforts (*2*, *6*).

It may be helpful for the project champion to show internal stakeholders that the project can be successful by using examples of past successful solar projects (*23*). It may also be beneficial to have external project champions in addition to the DOT project champion (*21*). This process may be strategic when partnering with external stakeholders, as noted on the proposed Caltrans right-of-way solar project. The project champion at Sacramento Municipal Utility District was essential for the project gaining support at the utility (*2*).

Staff Requirements

Due to the nature of solar energy projects, several state DOTs reported that they underestimated the amount of time needed to initiate and implement solar projects (*7*, *24*).

Reasons for project underestimation might include inexperience with solar projects; lack of resources, such as the time needed to address National Environmental Policy Act (NEPA) requirements; and need for specialized staff (*2*, *3*, *7*). If DOTs have multiple projects under development and are utilizing internal staff for project management and process tasks, there will be limits on staff availability and the number of projects that can be managed simultaneously (*6*).

Solar projects should be considered interdisciplinary projects that require team members from various sections within a DOT. Solar projects differ from typical transportation projects and raise unique issues not addressed by standard operating procedures and policies. Handling these issues involves coordination and communication between departments within the DOT, including real estate services, maintenance, operations, safety, environment, planning, and legal. It is important to involve representatives from each department early in the planning and decision-making process. Developing a consistent internal message within the DOT is important to minimize delays that can occur when different DOT offices have varying views or are giving conflicting direction (*2*).

Solar Energy Program or Project Manager

Many solar projects experience a great number of challenges, so federal guidance and other research suggest a full-time energy management position staffed by a DOT employee (*2*, *24*). The designated solar energy program or project manager should be responsible for site selection, oversight of the project budget and staff time needed for procurement coordination, request for proposal (RFP) development, identification of funding opportunities, contractor selection and contract development, and NEPA clearances and construction coordination (*6*, *7*). The project manager should have the authority to serve as the primary project lead and should be responsible for coordinating with appropriate departments, working closely with internal and external stakeholders, and serving as project liaison (*2*, *6*, *7*).

The project manager should be responsible for overseeing, coordinating, and integrating disparate tasks and driving much of the project schedule. The project manager should work in tandem with senior leadership to build a compelling vision and maintain support within the agency and among the various stakeholders to ensure project success. Depending on the scale and timeframe for solar project development and deployment, the project manager may be managing solar projects for a defined period while still holding other responsibilities within the agency (*6*).

Legal Counsel

Since solar installation projects may involve complex legal documents and various stakeholder participants, researchers recommend that DOTs use outside legal counsel or consultants to assist in developing contract agreements (*2*, *3*, *7*). The complexity and variability of solar installation projects require that project manager and staff have background knowledge in federal and state regulations for real estate, right-of-way, and utilities (*7*, *12*, *21*). Communication, coordination, and flexible and creative problem solving are also necessary requirements of staff to help ensure a successful project (*1*, *2*, *7*).

External Staff

Due to the complex nature of solar projects, many DOTs are unlikely to possess all the technical expertise needed internally. Therefore, coordination with outside experts may be beneficial, specifically when including discipline-specific experts for planning, design, finance, construction, and operations. Early in the program development phase, DOTs should assess their technical assistance needs and begin connecting with other state and federal agencies, as well as consultants and other private parties (*6*, *12*).

When third parties will be involved in the solar development project, they should be included with the project team early in the development process. They may have expertise and experience not available within the DOT, especially on initial solar projects.

Site Selection

Identifying and prioritizing potential sites for solar energy development is a critical element for project development. Taking a deliberate approach to site selection helps avoid limitations and incompatibilities that might prevent the completion of a project. Various strategies have been implemented to identify potential sites for solar energy development in the right-of-way. In most cases, states evaluate many sites using specific criteria, such as setback from the right-of-way, access for maintenance, cardinal orientation, and angle of inclination. This section covers considerations related to safety, size and space requirements, soil and slope, site orientation, glint and glare, site access, natural resource availability, grid connection, and legal considerations.

Safety Considerations

Safety considerations, including clear zone requirements, are paramount when selecting a site for solar installation. Clear zone requirements were Oregon DOT's main concern when choosing a site location for its solar facility in the right-of-way demonstration project (*2).* They are also FHWA's main concern for solar installations in the right-of-way (*7*). As a result, it is common for DOTs to place solar installations outside the clear zone and often behind an additional safety barrier (*2*).

Requirements for the setback and height of the solar installation should be established to help minimize impacts on the public. FHWA guidelines recommended working with appropriate departments to determine the location of the clear zone in relation to the proposed installation (*2*). Safety engineers and other DOT representatives can assist with finding the proper location for a solar installation in the right-of-way (*7*). In many cases, a setback distance of 30 ft from the shoulder of the highway can be a good starting point for a preliminary screening of potential sites (*2*). This preliminary screen will remove sites that are not suitable for solar installation and will help reduce the number of sites considered for a more detailed evaluation (*7*).

While a setback distance of 30 ft or larger is cited by several sources as a suitable initial project screen, a decision framework developed in Michigan recommends a distance of 50 ft or larger from the edge of the pavement (*5*). In addition, the framework highlights that a right-of-way extending 50 to 200 ft from the edge of the pavement can more safely accommodate infrastructure and provide access to solar production sites (*5*).

Setback and height requirements are usually site-specific and could vary depending on the type of solar technology used (*2*). Setbacks used by the Massachusetts and Oregon DOT solar projects were 60 ft (*2*). Previous right-of-way solar projects considered by Caltrans applied setback requirements to the travel lane and on-ramp of 8 ft vertical and 52 ft horizontal (*2*).

Size and Space Requirements

Another important consideration is selecting a site with sufficient size to accommodate the planned solar facility. The facility's size and layout should correspond to the space available in the right-of-way. Since the amount of land needed for an installation is related to the electrical capacity, it is important to consider the desired system capacity when selecting the size of the installation (*12*). According to study of land use by NREL, the average land use for solar is between 5.5 and 9.4 acres per MW_{ac}, and is dependent on the type of project (*25*). In general, the profitability of solar projects increases as the amount of power produced by the site increases, and many solar developers prefer to be involved with projects of 1 MW or larger (*7*). However, if a project is designed to supply power for a local load, it will be desirable to size the system to meet the needs of that load. In particular, facilities such as rest areas and maintenance yards are potentially suitable for solar installation projects (*6*).

Soil and Slope Considerations

Ground-mounted solar installations can be installed in locations with steep slopes—that is, slopes with a grade of 5 percent or higher. However, steep slopes might increase installation costs and can make maintenance more challenging, so overall, they are usually less desirable locations. Oregon DOT recommends considering sites where the slope is less than 5 percent (*12*).

The soil type of the selected location will impact the development of the solar site. Locations with cohesive soils are usually preferred over areas with a hard subsurface (*12*). These considerations, along with other land quality attributes (such as probability of flooding), should be taken into account when selecting a site because they may add additional cost to the installation or maintenance of a facility (*12*).

Site Orientation

The orientation of solar panels is an important element to consider when designing a solar installation. For projects located in the northern hemisphere, the best direction for the panels to face is usually south, though the price of electricity tends to increase around sunset, so mounting the modules with some tilt to the west may also be attractive.

Glint and Glare

Glint and glare are both reflections of light, with glint being defined as a briefer reflection of light than glare. For the purposes of this section, glare is used to describe both. According to

FHWA, some DOTs have concerns about how glare impacts the traveling public's safety (*2*, *6*). Further, the Federal Aviation Administration (FAA) recommends evaluating the reflectivity (or glare) of solar installations during the siting process (*6*, *26*). FAA recommendations are focused on solar installations at airports but are applicable to other installations that may impact other forms of transportation.

In general, solar panels are designed to absorb light rather than reflect it, which helps to minimize glare (*2*, *6*, *26*, *27*). However, research performed for Colorado DOT identified glare as one of the leading potential impacts related to solar installations (*28*). The research included performing computer modeling of site areas for glare impacts (*28*). Factors that might affect the impact of glare are the height, topography, orientation, tilt, and reflectivity of the solar panels, which can be reviewed and addressed when designing a solar installation (*6*). Glare from panels can be further reduced by adding an antireflective coating or using textured glass (*6*).

Oregon DOT held a public review and comment process to discuss the DOT's comprehensive appraisal of issues that may impact citizens, which included glare (*7*). On the proposed solar installation in Caltrans' right-of-way project, Sacramento Municipal Utility District commissioned a study looking into the risk of glare (*2*). Internationally, few countries have reported issues with glare. In Germany, solar facilities within or adjacent to the right-of-way are usually located behind safety barriers, and glare does not appear to be an issue (*27*). However, a group in The Netherlands is currently working on establishing a standard on how to install solar installations in a way that reduces several issues that may impact the public, including glare (*27*).

Ohio DOT has planned to evaluate the impacts of glare as one of its additional issues to consider for projects in the future (*2*). Oregon DOT reported that it does not currently have any mitigation requirements for glare and is looking to the federal government for guidance regarding solar glare (*29*). However, Oregon DOT recently installed a warning sign for a solar installation adjacent to the right-of-way (i.e., not located on DOT property) to warn roadway users of glare (*29*). Oregon DOT was concerned the glare might cause an accident and requested review of the solar installation's glare study (*29*).

A best practice is to include a provision in the agreement between the DOT and the site developer to alleviate issues related to glare if they arise in the future (*2*). As noted in the New Mexico DOT research report, it is important to identify potential concerns before they become an issue and take steps to mitigate those concerns (*7*).

Site Access

Site access is an important consideration for proper operation and safety. Access points should be designed to minimize public safety and security issues (*2*, *6, 12*). Several sources recommend having the site's access point located outside of the travel lane (*2*, *6, 12*). If the access point to the solar site is from the highway, a DOT should consider limiting site access—depending on the season or peak traffic—and should evaluate whether construction of acceleration/deceleration lanes would be beneficial (*2*).

Figure 1 to Figure 14 provide examples of site access for solar installations in Colorado, Massachusetts, Ohio, and Oregon. The three solar installation sites in Colorado appear to have access from the travel lanes, as shown in Figure 1 to Figure 6.

Figure 1. Aerial View of Solar Site Colorado 1 (Source: Google Earth).

Figure 2. Street View Showing Access to Solar Site Colorado 1 (Source: Google Street View).

Figure 3. Aerial View of Solar Site Colorado 2 (Source: Google Earth).

Figure 4. Street View Showing Access to Solar Site Colorado 2 (Source: Google Street View).

Figure 5. Aerial View of Solar Site Colorado 3 (Source: Google Earth).

Figure 6. Street View Showing Access to Solar Site Colorado 3 (Source: Google Street View).

Figure 7 shows a solar installation site in Massachusetts located between Interstate 90 and Stockbridge Road. The site can be accessed from either road, as seen in the blue outline on

Figure 7. Figure 8 shows a solar installation inside the Interstate 90 entrance ramp at Exit 13 in Framingham. The site can be accessed from the end of the entrance ramp, as shown by the blue outline. A third site located in Plymouth at the intersection of Route 3 and Long Pond Road is shown in Figure 9. The blue outline shows that the solar installation has access from a road or adjacent parking area. Figure 10 shows the access from the roadside, note the lack of a curb cut or driveway.

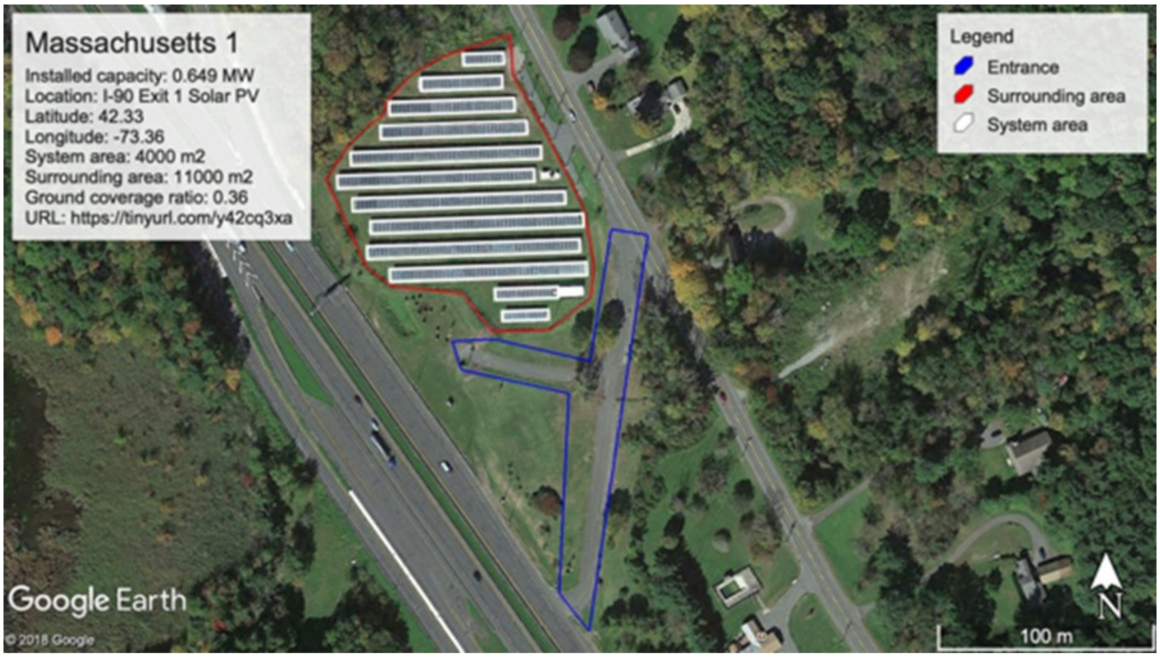

Figure 7. Aerial View of Solar Site Massachusetts 1 (Source: Google Earth).

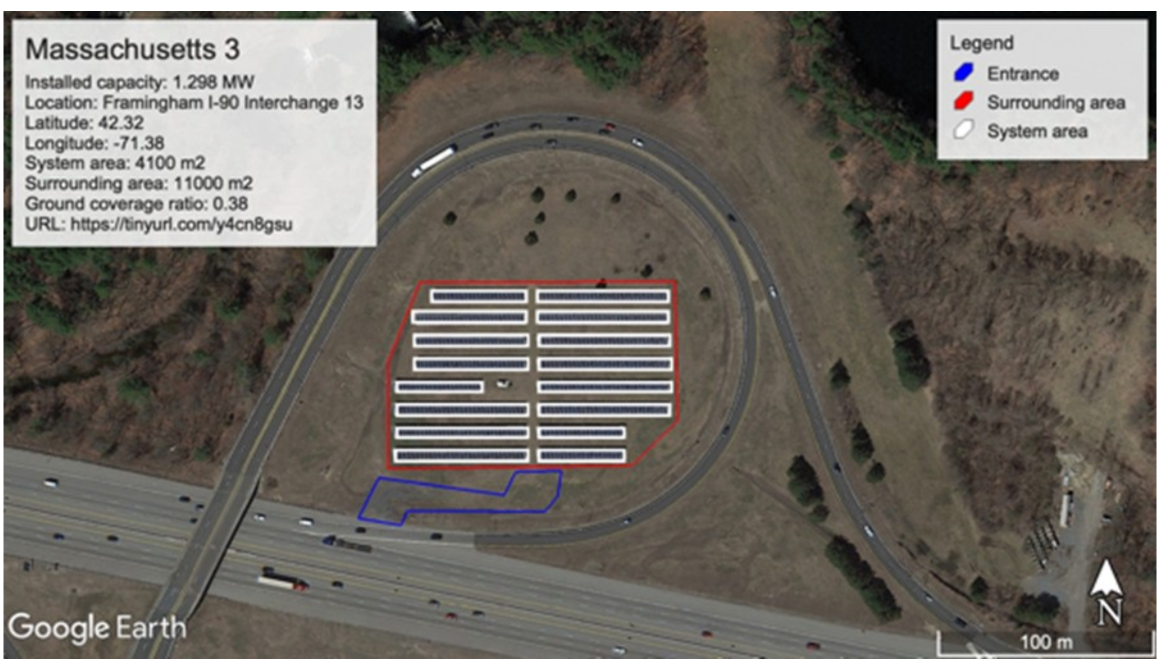

Figure 8. Aerial View of Solar Site Massachusetts 3 (Source: Google Earth).

Figure 9. Aerial View of Solar Site Massachusetts 6 (Source: Google Earth).

Figure 10. Street View Showing Access to Solar Site Massachusetts 6 (Source: Google Street View).

Figure 11 shows a solar installation in Toledo, Ohio, at the intersection of U.S. 280 and E Central Avenue. The site can be accessed from Galena Street, as shown in Figure 11. Figure 12 shows the access gate located on Galena Street.

Figure 11. Aerial View of Solar Site Ohio 1 (Source: Google Earth).

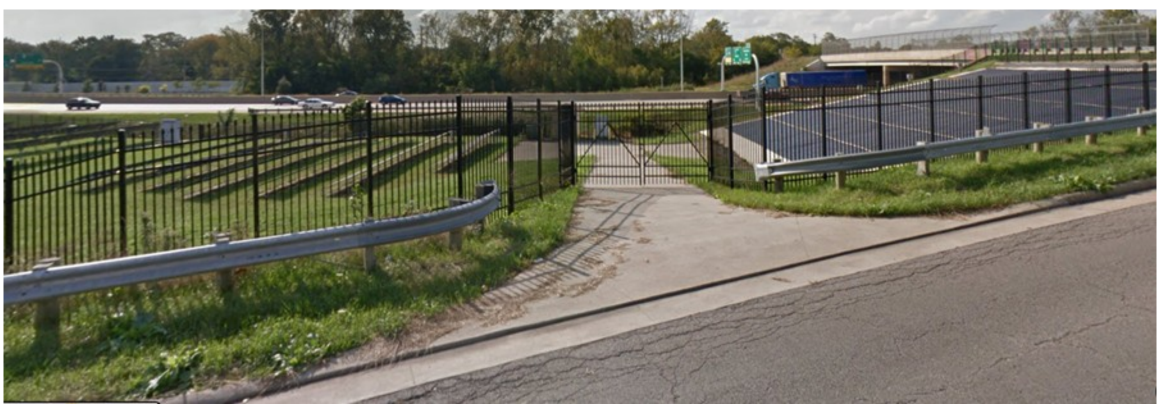

Figure 12. Street View Showing Access to Solar Site Ohio 1 (Source: Google Street View).

Figure 13 shows a solar installation south of Portland, Oregon, at the intersection of Interstates 5 and 205. As shown in Figure 13 and Figure 14, the site can be accessed from the highway using an access road that is located directly after the exit ramp from Interstate 205 west to Interstate 5 north.

Figure 13. Aerial View of Solar Site Oregon 1 (Source: Google Earth).

Figure 14. Street View Showing Access to Solar Site Oregon 1 (Source: Google Street View).

Construction of the solar facility might require additional access accommodations, such as gravel drives (*6*). In addition, any new highway access points on interstates need approval from FHWA, and any permanent or temporary access from travel lanes requires an encroachment permit from Caltrans (*12, 30*).

Availability of Natural Resources

A site's solar resource is one of the most critical factors in site selection. A site's solar resource is determined by insolation, or the amount of solar radiation received on a given surface area per unit of time. Most areas in the United States receive adequate solar radiation (*12*).

Maps that show available solar resources or that estimate the theoretical maximum electricity amounts can be helpful in determining potential solar energy generation locations. Right-of-way maps and other spatial data can be intersected to identify available right-of-way in areas with adequate solar potential. For example, preliminary screenings can be conducted remotely using aerial photography or satellite imagery. Developers and other agencies can assist DOTs with developing and analyzing the necessary geospatial data (*2*). Factors to consider when evaluating a site's solar potential include the following (*12*):

- Hills, vegetation, and buildings can create shadows that decrease the amount of solar energy reaching the surface.
- Sites should have southern exposure without shading and with limited vegetative cover.

In addition, drier microclimates with less frequent overcast conditions tend to have more solar energy available at ground level (*12*).

Grid Connection

Connection to the power grid is an important aspect of a solar project since most, if not all, of the energy produced by the solar installation will be used offsite. If a connection to the existing grid is cost prohibitive or otherwise not feasible, this site selection factor might be the key factor that excludes a site from further consideration. Therefore, it is important to consider grid connectivity early in the site screening process (*7*).

Based on past experience, researchers recommend considering both grid capacity and connectability when selecting potential solar sites (*7*). Preferably, a site under consideration should have a grid connection adjacent or very close to the site (*7*, *31*). As a rule of thumb, a potential solar site should be located within a half mile of the existing electric grid (*12*). There also may be opportunities to find sites that have a current electrical connection, which is usually an indication that the grid is close by (*12*).

Connecting a solar facility to the electrical grid is critical, and the lack of grid access may make energy production cost prohibitive and make the project or site selection impractical (*2*, *4*, *6*, *7*, *12*). On one of its solar projects, Oregon DOT reported that a great expense was required to secure a connection to the electric grid due to a tunnel under the existing highway (*7*). In addition, solar project developers should be aware that there is likely to be a grid connection fee, which, depending on the utility connected, might be substantial (*7*).

Just as important as connecting to the grid is considering the electrical capacity of the connection. Depending on the size of the solar installation, the grid needs to be able to accommodate a three-phase connection (*6, 12*). Even if a grid connection is close to the solar project site, the transmission line's capacity might be limited, which can add additional cost and delay the project's delivery (*12*). For example, both Massachusetts DOT and Oregon DOT reported problems dealing with connection capacity regarding solar projects (*7*).

As batteries become more advanced and microgrids become a common tool to improve resilience, Caltrans may find that off-grid, small, battery-powered microgrids may be useful when a traffic light or some other load needs to be powered and the grid is nowhere near.

Legal Considerations

Projects located within the right-of-way of interstate highways must conform to applicable federal regulations and standards. Experts within the DOT's right-of-way office should be consulted to review the relevance of current policies and practices related to renewable energy facilities in the state's right-of-way manual. As these types of projects become more common, modifications to current policies may be needed. At the beginning of developing a renewable energy program, consultation with state-level FHWA division offices will help ensure that all parties understand the framework for accommodating potential projects (*12*). An in-depth discussion of legal requirements and considerations is included in the deliverables for Task 4, Develop Content for Website of Current Rules, Regulations, and Policies.

Fair Market Value

Depending on the circumstances of right-of-way acquisition, DOTs are required to receive fair market value when leasing their property. FHWA allows non-highway uses of the right-of-way but requires compliance with 23 U.S.C. 156 and 23 CFR 710.403 that set the expectation of fair market value return for the use of the right-of-way (*32, 33*). Exceptions to the requirement to charge fair market value are defined in 23 CFR 710.403(e), which lists situations in which an exception may be approved. Similarly, FHWA policy guidance acknowledges the following (*34*):

> The regulations do provide an exception to charging fair market rent if the State DOT shows, and the FHWA approves, that such an exception is in the overall public interest for social, environmental, or economic purposes. This exception may be appropriate for activities that positively address climate change, contribute to improvements in air quality, and similar environmental initiatives.

Fair market value of the right-of-way may be difficult to define. Comparisons to adjacent private property may be insufficient or not accurate. On the one hand, the right-of-way is free from obstructions, and companies only need to negotiate with one landowner. However, private companies do not receive a property interest when leasing right-of-way from a DOT, and their facilities may be adjacent to a highway. Research is underway at the federal and state level to review this issue.

Fair market value varies depending on the use, size, and location of the right-of-way. Massachusetts DOT included a site lease fee of $17,500 per megawatt of installed capacity in its solar generation project. While Massachusetts DOT charges this lease fee, it also requires developers to include the fee in the power purchase agreement (PPA) rate schedule. Oregon DOT also includes a lease fee with its developer, but the annual payment is minimal (*6*).

Competing Right-of-Way Interests

One concern with installing solar generation in the right-of-way is the competing interests for the right-of-way. The primary function of a highway right-of-way is for highway purposes. Additional or secondary uses of the right-of-way or other property may be considered with highway purposes in mind. In many cases, there are several competing interests for the right-of-way, including other types of renewable energy sites in addition to solar energy. Other interests in the right-of-way include, but are not limited to, public utilities, private utilities, temporary utility installations, small cell nodes, air leases, and other potential future uses. Installation of solar facilities may preclude other uses of the right-of-way.

Patent Issues

The systems that produce, collect, and transmit renewable energy are usually patented, and patent holders are entitled to collect license fees for the use of the methodologies and techniques covered by their patents. Instances have occurred wherein a public entity paid for licenses for a renewable energy technology in the right-of-way when it was not clear that such licenses were required. DOTs should consult with a patent or intellectual property attorney for assistance in determining the applicability of patents. Patent issues may increase project costs and timelines (*2*).

In addition, DOTs have sometimes been approached by patent holders late in the development process for renewable energy sites. The patent holders informed the partners that they are entitled to collect license fees for the methodologies and techniques covered by the patents. In several cases, the partners negotiated a license fee to resolve the issues instead of challenging the patent in court in an effort to avoid legal fees and project delays (*2*).

Project Procurement

Preparing individual RFPs for solar installations takes more time than preparing an RFP that includes multiple solar installation sites. However, experienced DOTs reported that RFPs that included multiple installations led to overpricing, an increased number of changes orders, and a more complex project development process (*6, 7*).

Solar project owners often expect that a publicly released RFP will reach and be seen by many qualified developers. In practice, that occurrence is usually not the case (*6*). Since publicly releasing the RFP will not guarantee highly qualified developers will submit a proposal, it is a good practice to actively advertise to qualified developers in addition to releasing the RFP publicly (*6, 7*).

Some state DOTs reported issues with generating interest and receiving responses from developers regarding solar project RFIs and RFPs (*7*). One way to advertise and generate interest for an RFP is to contact developers who would have been expected to but did not submit a proposal and to inquire why they did not respond to the RFP (*6, 7*). Most developers will be able to provide some feedback on how to make the RFP more appealing or how to make it easier for the developer to respond. Another option to make it easier for developers to respond to an RFP is to define the value of financial incentives, which simplifies a vendor response in comparison to having the vendors define the value of financial incentives in their response (*6*).

Partnership Models

Agencies use several types of partnership models to build, operate, and maintain solar energy installations in the right-of-way. Most agencies partner with third parties when developing solar energy sites. Public agencies have no tax burden and cannot take advantage of tax-related financial incentives for investments in photovoltaic solar systems. As a result, DOTs might partner with private-sector firms to design, finance, install, own, and operate a photovoltaic solar installation on the DOT's property to take advantage of tax incentives. The DOT benefits by avoiding upfront capital investment and ongoing operating and maintenance expenses and securing a long-term price for electricity. The private-sector partner benefits from receiving revenue for electricity sales and by capturing tax benefits and other financial incentives. Some agencies have explored owner-operator models, as well as purchasing the installation back from a private partner after a certain amount of time (*6*).

Regardless of the type of agreement, contingency plans are advisable in the event business partners are no longer able to work with the DOT or maintain the infrastructure. In addition, there may be economic concerns related to awarding contracts and developing partnerships with private entities. DOTs must ensure the process is fair and competitive and that it balances societal and private interests (*5*). The sections below cover in detail the partnering models that are commonly available to DOTs to develop solar energy projects in the right-of-way, including public-private partnerships, third-party business models, PPAs, and net metering.

Public-Private Partnerships

Under a public-private partnership, a DOT enters into an agreement with a private-sector partner to design, finance, build, own, and operate the solar installation on DOT property. The DOT may enter into an agreement to purchase the electricity generated by the system or enter into a net metering agreement wherein a utility purchases the power generated. These agreements are discussed in more detail below.

In a public-private partnership, the DOT benefits by avoiding upfront capital investment and ongoing operation and maintenance expenses. DOTs are generally prohibited from owning equity in a private enterprise, so they usually do not own the solar assets in public-private partnerships. If desired, ownership of the solar assets can be transferred back to the DOT at a later point in time (*12*). The private-sector partner benefits by receiving revenue from electricity sales and by capturing the tax benefits and financial incentives available for developing solar energy projects. Frequently, the private-sector partner comprises a joint enterprise between a solar developer and an investment partner. The solar developer has the expertise to manage the engineering, procurement, construction, maintenance, and operation of the system, while the investment partner provides capital to finance the project and the tax liability to take advantage of tax credits (*12*).

If the local utility is not an active partner in the public-private partnership, it is important to coordinate with the local utility early in the development process. Coordination is particularly important if a project does not identify a customer for the electricity that will be produced (*1*). Several DOTs have reported delays when not including the local utility during project development.

Third-Party Business Models

Three variations of the third-party financing mechanism that relate to the dynamics between the developer and the tax equity partner are discussed below. The use of these agreements facilitates financial relationships with solar developers and tax equity partners to take advantage of tax incentives but does not offer DOTs assurance that they can "reach through" the partnership structure to a responsible party to ensure compliance with the underlying solar project agreement. It is therefore critical that the DOT's underlying agreement includes provisions to ensure that a responsible party will be accountable for performance under the agreement (*12*).

- **Partnership Flip Model.** In the partnership flip model, the private-sector solar developer and the investment partner form a special-purpose entity, usually a limited liability corporation (LLC), for the sole purpose of developing and owning a particular solar project. The DOT enters in agreements to host the system and purchase electricity from the LLC (*12*).

- **Sale-Leaseback Model.** In the sale-leaseback model, the solar developer builds a project and upon completion sells it to an investment partner. The investment partner and the developer, or LLC, enter into an operating lease (*12*).

- **Pass-Through Lease.** The pass-through lease is similar to the sale-leaseback model except that the lessee and lessor roles are reversed. This model is sometimes referred to as an inverted lease. In this arrangement, the developer builds the project and then leases it to a tax equity investment partner. The DOT enters into agreements with the investment partner to host the system or purchase electricity (*12*).

Power Purchase Agreements

In addition to agreeing to host the solar generation system on DOT property, many DOTs agree to purchase the electricity generated from the site by signing a long-term PPA. DOTs benefit from this arrangement by securing long-term predictable prices for electricity, often initially at a price lower than current electric rates. It should be noted that these agreements are not permitted in every state, and in some states the permissibility of using a PPA is unresolved. DOTs should consult with legal counsel before entering into binding agreements (*12*).

Developers want to find a secure market for the solar power produced. Long-term agreements (20 years or more) from utility companies are becoming less frequent, which make developers dependent on the wholesale energy market to generate revenue (*35*). In addition to shorter terms, the solar PPA market is defined by low energy prices, and corporate PPAs are becoming increasingly prevalent (*35*). Corporate PPAs began as standard PPAs but have evolved in a way that shifts more of the risk onto the developer (*35*). This is mostly achieved by basing the PPA on the hub price, which reflects the market price of power, instead of the node price, which is typical for a standard PPA (*35*). The node price of power may be inflated due to factors outside of the control of the developer. One common factor affecting the node price is inefficiencies in the grid infrastructure (*35*). Furthermore, corporate PPAs are usually 10 years in length compared to 20 years or more for a standard PPA (*35*).

A few ways developers are managing the risk is through the use of fixed-volume price swaps and proxy revenue swaps. In the future, a more connected grid infrastructure would allow for more energy transfer between states, and the use of energy storage would help stabilize the market for solar energy. This would reduce the risk of solar energy projects and could lead to an increase in investment (*35*).

Net Metering

Net metering is a process by which electric utilities provide a utility bill credit for electricity generated by a system tied to the grid that is in surplus of what is consumed by the customer. Forty-one states and the District of Columbia have adopted rules that require electric utility companies to provide net metering credits. The rules vary widely by state, but the rules generally affect the rate at which utilities purchase excess generation, the length of time and period for which credits are valid, and the maximum allowable installation size. In most states, net metering rules only allow a solar photovoltaic system to accrue bill credits against the electric service meter through which it is interconnected—thereby limiting the photovoltaic system's size. Some states and utilities, however, allow customers to aggregate multiple meters and thereby offset their electricity consumption at several locations (*12*). During the review of DOT practices, several instances were identified in which utility companies requested the size of solar installations to be reduced prior to authorizing a connection to the grid, essentially to balance the amount of electricity that would be sent to the grid in excess of what was consumed on site.

The rate a utility agrees to pay for excess generation will typically be the regular retail rate for energy, the utility's avoided cost rate, or the utility's wholesale generation rate. The utility's avoided cost rate is the price the utility would otherwise have to pay to acquire new generation resources. The utility's wholesale generation rate is the price the utility pays for existing generation. Of these rates, the regular retail rate for energy typically offers the customer the most advantageous pricing, while the wholesale generation rate is typically the least advantageous. In many cases, utilities only provide bill credits to offset the part of the monthly electric bill associated with power consumption. Even if a solar photovoltaic system provides all electricity needed by the customer, the customer will continue to receive a bill from the utility for basic service charges. In addition, net metering rules often restrict how long a customer can maintain a balance of bill credits. A common arrangement is to allow a customer to carry forward unused credits to the next billing cycle for up to 12 months, after which the unused credits are forfeited. Forfeited credits are often directed toward low-income utility assistance programs (*12*).

Proposal Scoring Methods

Several DOTs preferred the use of a best-value scoring method over a low-bid method when selecting developers (*6, 7*). DOTs reported that best-value scoring is preferable over selecting the lowest cost, which may lead to a selection that does not align with the environmental and sustainability goals of the project (*1*, *2*).

Oregon DOT implemented value-based criteria when evaluating proposals (*12*). The DOT considered the contribution the project would have on the state's values and public interest by considering the commitments to the state's sustainability policies in addition to the technical and corporate qualifications (*1*, *2*). The DOT might borrow a value-based criteria from another department or agency within the state and revise to match the DOT's requirements if one is not already in use (*1*, *2*).

If a low-bid method is necessary, DOTs suggested adding more stringent requirements. Examples might include a requirement for proof of qualification and experience and more detailed specifications (*6, 7*). Regardless of the method chosen, vendor selection should focus on getting the most value for the DOT from the project (*7*). Due to the lengthy procurement process at some state DOTs and the solar development environment, often the selected developer might not be available once the solar project is ready for implementation (*7*). It therefore is a good business practice to select a developer that has sufficient experience with solar installations and an established place in the market (*7*).

Recommended Contract Provisions

Including third-party performance requirements in solar project contracts is a good practice. The performance requirements as well as penalties should be clearly defined (*6, 7*). It may also be strategic to state resolutions to certain scenarios or have a contingency plan in place (*6, 7*).

A good contracting practice is a provision in the project agreement that provides the DOT a review and comment period for design and construction submittals (*6, 12*). Some of the more common approvals and permits include a design review permit, a utility accommodation permit, and a utility interconnection approval (*6, 12*).

Post-Award Recommendations

After selecting a construction contractor for the installation, it is good practice to have the contractor review the design plans and recommend any design changes before construction proceeds (*6*). The DOT should aim to coordinate the timing of construction activities to ensure that impact on the traveling public is minimal (*6, 12*). Also, the DOT should coordinate the timing with the construction contractor to make sure the project stays on schedule and no major milestones are missed (*6, 12*).

Project Commissioning

After construction is complete, commissioning needs to take place for the solar installation, which assures that all components of the solar system have been installed and tested to function as designed. At this point, the developer might perform final checks for quality to ensure the facility operates according to the operational requirements (*6, 12*). These checks should include the installation's electrical system to ensure that all codes and standards have been met (*6, 12*).

Although the developer is responsible for commissioning, the DOT should have an interest in the installation and its commissioning since the installation is located on the DOT's right-of-way (*12*). It is best practice for the developer to notify the DOT of any issues and the resolution of the issues during the commissioning process (*6, 12*). Once commissioning is complete, the developer should provide a final commissioning report to the DOT (*6, 12*).

Once commissioning is finalized, and with approval from the electrical utility company, the solar installation can begin sending electricity to the power grid (*6, 12*). Once the solar facility begins operating, the DOT should perform an inspection with the developer (*12*). This inspection will produce a list of issues that the developer needs to resolve before the project can be considered complete. Once the issues have been resolved, the developer should send the DOT a letter certifying the project is complete (*6, 7, 12*).

Site Operation and Maintenance

Assuming there is no damage from external factors, solar energy installations should require minimal maintenance, but maintenance should still be a concern for DOTs (*2*, *6*, *27*). The following sections discuss the following topics regarding maintenance of solar facilities: planning and design, external factors, maintenance contracts, site security, and system monitoring.

Planning and Design

An FHWA peer exchange resulted in a few recommendations for site design with regard to slope and mowing. If the design follows the natural slope of the land, erosion issues can often be minimized (*23*). In addition, planting low-growing grass species can help minimize the need for mowing (*2*). The site design should also include the impact on other DOT maintenance practices (*5*). In unison, these recommendations should reduce maintenance costs.

Another area of consideration for maintenance is the solar panels themselves. Required maintenance of solar panels due to general upkeep or failure of a panel might result in downtime and loss of revenue. One way to reduce downtime from inoperable panels is to store additional solar panels on site (*23*). The additional panels can be swapped out to keep the array operational. Cleaning of solar panels should not be necessary with proper design and planning of the solar facility. DOTs reported that, in general, washing solar panels did not result in any meaningful increases in power generation (*27*). Oregon DOT reported that if panels are installed at an angle to allow rain to run off, occasional rain is sufficient to keep the panels clean and operational (*2*). In locations with infrequent rain, performance reduction from soiling usually does not exceed 10 percent, but performance losses up to about 20 percent may occur at certain times of the year if the panels are not cleaned during the dry season. Sites with consistent rain may expect < 3 percent losses related to soiling.

Previous research by Caltrans resulted in a recommendation to carefully review solar design documents to ensure that the design meets the DOT's requirements and that considerations for maintenance are addressed by the design (*24*). Since documentation provided by construction contractors after project completion may not provide adequate information for proper maintenance, design documents can often be used as a supplemental source of information for maintenance activities (*24*).

External Factors

The two major external factors that affect the maintenance of solar installation are human interference and extreme weather events. Human interference factors frequently cited include vandalism and theft, which can be mitigated by appropriate security measures (*7*). Ensuring security measures are in place should minimize or eliminate vandalism and theft. Extreme weather may not be as easy to curtail, but a few strategies can help reduce damage in such an event. For example, the impact of a lightning strike can be mitigated by installing transient voltage surge suppressors (*7*). Further, proper installation should minimize the impact of high winds on panels, and access to necessary equipment should reduce downtime in case of extreme weather events (*7*).

Maintenance Contracts

State DOTs often use contractors, who might be exempt from needing an encroachment permit under certain circumstances, to conduct maintenance activities (*30*). When long-term contracts are used, it is important to monitor contractor performance. Expectations for contractor responsiveness should be included in the contract since performance may decrease over the life of the contract (*7*). It is also important to ensure contractors and other maintenance personnel are aware of maintenance and access issues (*7*).

Along with regular monitoring for repairs, annual site inspection is recommended. Tasks that should be performed during the site inspection include the following (*6, 12*):

- Clearing away debris or vegetation from around the system.
- Verifying structural integrity and electrical system output.
- Checking for damage and corrosion issues.
- Making any necessary repairs or performing maintenance.

Following the site inspection, a copy of the inspection report should be provided to the DOT (*6*).

Site Security

Site security is an important consideration to ensure continuous operations of the solar site. Most solar installations are not hidden from public view and can be a target of theft and vandalism (*12*). Security measures of existing solar sites usually center on prevention of theft and vandalism. For example, many sites include a full perimeter fence. In the case of Oregon DOT's solar project, the DOT selected a full-height fence with triple-strand barbed wire (*2*). A 6-ft fence with barbed wire and locked gate access may be permitted depending on the DOT's policy (*30*). In the case of Caltrans' planned solar project on Highway 50, the use of a full perimeter fence was not feasible, so partial fencing and protective landscape were considered

(*2*). Other prevention measures to secure a solar installation can involve the use of tamper-resistant bolts, countersunk screws, and fully enclosed wiring, which make removal and tampering tougher and more time consuming (*2*).

Additional security of the solar site can be attained by active site monitoring. For the Oregon solar project, Portland General Electric uses sensors and cameras to identify when the entry gate is being operated, if a fence has been breached, and if there is movement within the installation area (*2*). It is also advisable to have contact or security protocols in place in the event of a security breach. For example, Oregon DOT's security protocol is to notify State Police and then Portland General Electric if a security issue arises (*2*). Active site monitoring along with passive prevention measures can create a comprehensive security strategy and discourage potential thieves.

In addition to prevention, security measures mentioned in the literature are education and theft recovery. Education might involve the placement of warning signs to discourage theft (*2*). Informing potential perpetrators about some of the security measures or consequences might help prevent trespass and theft. To facilitate theft recovery, Portland General Electric implemented a proprietary theft deterrent product at the Oregon DOT solar project site that allows for the recovery of stolen electronic equipment (*2*).

Design considerations can further contribute to the security of a solar site and may lead to important features that will make the installation inherently more secure. One such design aspect was seen on the proposed Caltrans right-of-way solar project. Because of the possibility that the panels may be used for shelter, solar panels were designed to be installed close to the ground surface (*2*).

System Monitoring

It is important for a solar installation to have a monitoring system in place to maintain proper operation and maintenance of the solar installation. A monitoring system allows operators and other stakeholders to observe system performance and act if issues arise (*26*). Online monitoring of the solar system allows for the timely identification of necessary maintenance as well as the opportunity to improve performance (*12*, *24*). System monitoring requirements can be included in the maintenance contract for the solar site.

Recommendations for proper solar monitoring include tracking key system performance indicators and using updated software and technology (*12*). Tracking key performance indicators allows the user to see patterns and issues as they arise, which enables the user to possibly reduce operation and maintenance cost, maximize performance, and continually improve the operation of installation (*36*). The use of updated software and technology helps with overall operations and maintenance by improving reliability of the system, and the use of high-quality sensors is important for dependable monitoring (*36*). Monitoring systems continuously evolve, especially in the area of asset management, data analytics, and remote diagnostics and imaging (*36*). The presentation of the data and openness of measurement procedures are additional important system monitoring considerations (*36*).

Additional Recommendations

Project Timeline

Project timelines can be difficult to predict. The first implementation of a new project type is likely to take longer than expected (*7*). Timelines of a few months to a year for planning through commissioning are typical but depend on whether the project is done in-house, covers multiple sites, or requires agreements between different stakeholders (*6*). Timelines can also be influenced by team availability and resources, federal and state policy, contracting and construction seasons, and financing (*6*).

Addressing Issues Early

Several agencies stressed the importance of identifying and addressing potential issues early in the project. Sacramento Municipal Utility District developed a risk matrix for the proposed solar facility in the right-of-way project that reflects all potential issues affecting a project and a process for updating the risk matrix as some issues are resolved and new ones arise (*2*). Virginia DOT developed risk registers listing risks that may affect different site types (*37*). Projects at Virginia DOT facilities were judged to be vulnerable to changes in state and federal renewable energy policies and tax credits, lease term limits, and offtake agreements. Projects on Virginia DOT primary/secondary right-of-way were judged to be vulnerable to changes in state policy, rushed implementation, scope definition, and program risk. Projects on Virginia DOT interstate right-of-way were judged to be vulnerable to project approval, land-use regulations, environmental considerations, and site access and security.

Decommissioning

The productivity of solar panels degrades over time, so at some point it becomes more cost effective to decommission the system. Several different options are available when solar installations approach the end of their useful life. In a buyback or purchase arrangement, the DOT will return or sell the system components to the manufacturer or third-party developer when the system reaches the end of its contracted or warrantied life (*6*). Solar components have some salvage value, although the exact amount varies by site. Oregon DOT found that the salvage value is often similar to the decommissioning cost (*6*). Oregon DOT returned solar panels to the manufacturer and paid a recovery/disposal fee.

In Vermont, the state Buildings and General Services has developed agreements to purchase the solar photovoltaic system from a third-party developer in year seven. Seven years is a typical contract warranty period, but most solar facilities will continue to perform beyond the warranty period (*6*). If solar components are to be sold or purchased, the DOT is advised to assess the condition and value of the system at the time of sale to ensure that the price is appropriate.

DOT Solar Deployments in the Right-of-Way

Several DOTs have installed renewable energy technologies, and of those DOTs, most have implemented solar power. Renewable energy projects consist of ground-mounted and rooftop-mounted solar panels. Ground-mounted solar panels are often placed along the right-of-way and at rest areas, while rooftop-mounted solar panels are installed on carports, maintenance buildings, rest areas, or other facilities (*38*).

There is a small but growing number of DOTs that are beginning to utilize highway right-of-way for renewable energy production facilities. Oregon pioneered the idea in 2008, becoming the first agency in the United States to install a solar panel array along a highway right-of-way. Over the next several years, Ohio, Colorado, and Massachusetts installed solar panels in the right-of-way.

The FHWA Office of Real Estate Services maintains a map of right-of-way renewable energy projects, including solar, wind, and hydroelectric projects. DOTs are encouraged to submit projects in their states for inclusion in the map (*39*). Figure 15 shows the current map of renewable energy sources in highway right-of-way (*38*).

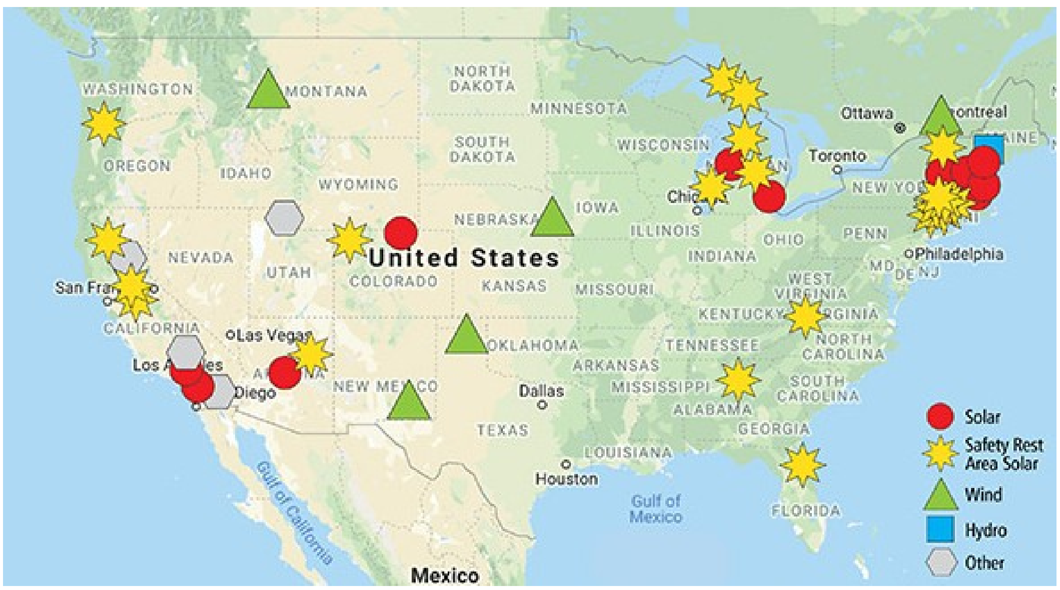

Figure 15. Map of Renewable Energy Projects in Highway Right-of-Way in Various States (*38*).

The following sections describe DOTs' experiences with installing solar power in the right-of-way. Specifically, the review presents information from Hawaii, Massachusetts, Ohio, Oregon, and Vermont.

Hawaii DOT

In 2015, Hawaii committed to achieving 100 percent renewable electricity generation by 2045, which would make Hawaii the first state in the nation completely powered by renewable electricity (*40*). To achieve this goal, Hawaii is relying on a combination of wind power, solar power, geothermal power, hydropower, and biofuels. Currently, Hawaii obtains about 20 percent of its electricity from renewable energy sources. Challenges that Hawaii DOT faces with installing solar power are high land values, limited amounts of land available, and impacts on sensitive ecosystems and wildlife (*39*).

Hawaii DOT is installing solar panels to help achieve the goal of obtaining 100 percent renewable energy. In 2013, Hawaii DOT entered into an energy savings contract with a 20-year performance period for 12 state airports (*41*). The contract guarantees an energy use reduction of 49 percent by installing energy efficiency measures that include solar energy generation. The contract includes annual payments by the contractor to Hawaii DOT if savings are not achieved. Over two phases, solar panels were installed, producing a total of 8 MW of power. The solar energy produced provided a 7–10 percent return on the contract value. Hawaii expects a total energy cost savings of $776 million over the course of the contract. Several lessons learned were noted that might be applicable to other solar power installations (*7*):

- Include responsiveness expectations in contracts to ensure responsiveness does not decrease over time.
- Be aware of unnecessary energy saving verification actions written into contracts.
- Energy-performance-savings contractors operate under risk and will strive to take advantage of any cost opportunity.
- Include cost contingency plans and ensure unused funds are returned to the client.
- Ensure the contractor has a transparent subcontractor program that specifies bids and expenditures.

Hawaii DOT did not use federal funds or new construction for these installations. Therefore, the projects did not require review through the NEPA process.

Massachusetts DOT

Massachusetts DOT has implemented several solar energy projects using public-private partnerships. Contractors lease Massachusetts DOT property that has been approved for solar installations, and Massachusetts DOT purchases power from the contractor at fixed rates for the duration of the lease. Massachusetts DOT keeps all net metering credits, while the developer keeps all solar power generation incentives. Massachusetts DOT noted several benefits of using this arrangement (*42*):

- There are no upfront capital costs for the state.
- The private partner can fully utilize federal tax incentives.
- The DOT receives a favorable electricity rate schedule for the contract period.
- The DOT realizes energy savings through net metering.
- The DOT realizes lease revenue for the developer's use of state properties.

Massachusetts DOT began solar energy production in the state right-of-way with a pilot project that was installed in 2012 (*42*). The pilot project consisted of installing 325 solar panels on a parcel adjacent to a district administrative building along an interstate highway. Massachusetts DOT then began a highway right-of-way solar program to install solar energy sites along various other highways. Phase I of the project includes 10 parcels. In total, the highway solar projects have a potential capacity of 7.2 MW, with an attainable capacity of 5.5 MW due to regulatory and site condition restraints (*42*). The projected energy output of the sites is about 6.2 million kWh annually (*42*).

To implement the program, Massachusetts DOT updated its utility accommodation policy to include guidelines for renewable energy technologies, safety criteria, design standards, project development, compensation requirements, and relevant license and lease agreements (*43*). Massachusetts DOT then worked with a consultant to screen potential sites for its solar generation potential by considering shading, topography, existing drainage, utilities, proximity to electricity transmission lines, environmental concerns, any conflicting use, and visibility. Of more than 600 possible locations, 10 were selected for the installation of ground-mounted solar panel systems (*1*).

As of August 2018, the solar sites have produced 10,750 MWh of electricity, which has resulted in a savings to Massachusetts DOT of over $1 million. Massachusetts DOT expects to save approximately $525,000 annually in addition to the $75,000 received in annual lease payments for the sites (*38*). In total, Massachusetts DOT expects to save at least $15 million over the contract period, including about $2 million in rent from leases on state property (*43*, *44*). Massachusetts DOT charges a lease fee of $17,500 per installed megawatt of capacity (*6*).

Massachusetts DOT noted several benefits to developing multiple solar power sites across the state under one program (*43*, *44*):

- Only one procurement document and bid are required.
- The owner and operator may be able to purchase equipment and services in bulk at a discount.
- Construction and mobilization can occur at multiple sites simultaneously.

Massachusetts DOT did not report any significant issues related to its solar installations. Minor issues reported included aesthetics and glare, both of which were resolved through public involvement (*6*).

Ohio DOT

In 2008, the Ohio Legislature established a renewable energy portfolio standard that requires utilities by 2025 to provide 11.5 percent of their retail electricity supply from alternative energy resources, of which 0.46 percent must be generated by solar energy resources (*45*). Shortly thereafter, Ohio DOT was granted the authority to lease its right-of-way for the deployment of alternative energy technologies. Currently, Ohio DOT has several renewable energy projects underway in highway right-of-way and on other DOT-owned property. In 2010, Ohio DOT installed a 100-kW grid connected solar array in the right-of-way of an interstate (*2*). Electricity is generated to offset a nearby bridge's lighting consumption (*1*). Ohio DOT noted several lessons learned from implementing renewable energy projects (*2*):

- Ohio DOT ownership of renewable energy facilities is not a sustainable business model. Ohio DOT advocates for a utility or private partner to own and operate facilities, with Ohio DOT purchasing energy through a power purchase agreement in future projects.
- Developing renewable energy projects requires input from a cross-section of stakeholders.
- Developing renewable energy projects requires a full-time DOT project manager.
- Educating DOT staff is integral to success. Securing internal support from leadership, districts, and departments is an important element to successful implementation.

The project was funded through state planning and research funds. As part of the project, the University of Toledo evaluated the effectiveness of installing solar sites along the highway right-of-way in Ohio. The field demonstration will be used to evaluate glint and glare impacts and to identify additional issues to consider in future projects, such as the impact of snow melt and ice damming (*2*).

Oregon DOT

In 2007, Oregon's governor directed state agencies to meet 100 percent of their electricity needs with renewable energy by 2025. In 2008, Oregon DOT became the first state agency in the United States to install a solar panel array along a highway right-of-way. This demonstration project consisted of 594 ground-mounted solar panels at the interchange of two interstates. The panels produced about one-third of the electricity needed to illuminate the interchange (*2*, *44*, *46*).

The original project selection criteria included locating panels outside of the clear zone, selecting an area that would not be improved in the foreseeable future, and selecting an area that was within the utility company's service area. The site was selected because there was available land outside the clear zone that was south-facing, experienced little shading, and was in a highly visible area (*2*).

The pilot project was financed through a public-private partnership with a utility provider and other public and private entities. An LLC that owns and operates the facility was created. Oregon DOT partnered with a separate entity to design, construct, and install the solar panels. The public-private partnership allowed for the use of federal and state tax incentives for renewable energy projects. The utility company was able to use the project to offset carbon emissions from coal-fired power plants, as required by the state. Oregon DOT entered into a site license agreement to allow the developer to install the solar system on state property. Oregon DOT also entered into a PPA to purchase electricity at the same rate the agency pays for electricity from other sources on the grid. Both agreements have 20-year terms (*2*, *47*).

As a result of the success of the first project, a second solar panel installation was built in 2011. This project consisted of installing a solar array at a 7-acre site adjacent to a rest area along an interstate. A third project includes installing a 3-MW solar panel system at an Oregon DOT operations and maintenance staging site. Several agencies have reached out to Oregon DOT for information about these projects. As a result, Oregon DOT created a guidebook for DOTs to use to develop solar photovoltaic systems in the highway right-of-way. The guidebook covers four main topics: understanding the context, developing a solar highway program, developing a solar highway project, and assessing project feasibility (*12*).

Oregon DOT recommends addressing several topics when developing solar power generation sites (*3*):

- Identify state-specific policy context. Build understanding of state-specific policy landscape for renewable energy development, including net metering rules, solar power purchase agreements, and financial incentives.
- Evaluate business models. Research and understand variations in public-private partnerships and business models, and the associated agreements.
- Coordinate with the FHWA Division Office to determine permitting framework (i.e., utility accommodation or right-of-way use agreement).
- Identify and prioritize candidate sites. Identify a list of potential sites that warrant further evaluation. Screen sites based on solar energy potential, land requirements, electric grid access, and environmental resource impacts.
- Assess candidate site feasibility. Include an on-site solar resource evaluation, a preliminary environmental screen, and a preliminary economic analysis regarding project cost effectiveness. Compare project expenses and revenues to calculate a saving-to-investment ratio or simple payback period.
- Conduct public involvement and communication. Inform and gather input from project stakeholders and the public.
- Identify and select a solar developer. Use procurement tools such as requests for information, requests for qualifications, or requests for proposals to identify potential solar developers.
- Coordinate with the solar developer to secure necessary permits and approvals to deliver and implement the project.

In addition, Oregon DOT noted the need for a project champion and a project manager. Developing a solar program and projects required substantial time and unique skills. Leadership buy-in was critical to successfully implement the solar generation projects.

Oregon DOT allows six to 12 months to develop a solar project and then six additional months for construction. Some of the costs associated with developing solar generation projects can be offset by public-private partnerships. However, some funding is needed for internal staff time and external consulting and legal services (*12*).

Vermont Agency of Transportation

The Vermont Agency of Transportation (VTrans) has developed several solar projects that total 330 kW of capacity. Projects include solar panels at an airport, solar panels on 13 VTrans garages, and one right-of-way solar project on a U.S. highway. In 2016, VTrans developed a solar plan to explain to the public why VTrans is interested in solar energy, describe the process for identifying suitable right-of-way solar sites, and outline information about financial and technological specification (*6*). In addition, VTrans amended its utility accommodation procedures by adding a new section on renewable energy generation to better facilitate solar development in the right-of-way (*20*).

VTrans is realizing significant cost savings from its solar installations. For example, the installation at an airport is expected to save VTrans $400,000 over 30 years. In addition, installation costs are decreasing every year, which will increase savings from future installations (*43*, *44*). VTrans noted several primary reasons for installing solar photovoltaic systems (*6*):

- **Agency cost reductions and financial feasibility.** Inadequate revenues from traditional sources such as fuel taxes limits the agency's ability to carry out its mission. In order to maintain the level of service to the public that depends on the VTrans system, operational cost avoidance and alternative revenue streams must be developed. Implementing solar projects can reduce agency operational costs, and those cost reductions can be allocated to other essential agency activities. The current energy landscape of renewables in Vermont coupled with the financial facets of solar photovoltaic projects, particularly pricing and project lifecycle, allow for projects to be feasible now that may not have been just a few years ago.

- **Resilience and continuity of service.** Distributed solar energy facilities have the potential to provide the essential power for VTrans to continue operations when the electrical grid is down during and following disaster events to provide essential services for first responders and to reestablish normal life for the rest of Vermont. Many things can disrupt the grid, including storms, extreme heat or cold that can cause rolling blackouts, cyberterrorism, and more.

- **Reduction in the future effects of climate change.** In order to limit the magnitude of future climate change impacts, mitigation of greenhouse gas emissions from fossil fuel electricity generation is important.

- **Policy alignment.** Policy directives at the agency, region, state, and federal levels require or encourage VTrans to participate in the shift to renewable energy sources and clean transportation targets, particularly Vermont's 2050 energy goal.

- **Vermont's need for new clean electricity supply and VTrans energy use.** In the past few years, Vermont has deployed solar photovoltaic systems in substantial quantities.

This growth has been spurred by the opportunity for a greater percentage of local, renewable power. In part, the closure of the Yankee Nuclear Power Plant left a vacancy in electrical power production, and Vermont relies upon a majority of its electricity generation from outside its borders. Vermont state policy and initial net metering rules assisted in this growth of solar photovoltaic systems and will continue do so, albeit at a slower pace of implementation.

- **Reduced need for solar sites on agricultural land and scenic viewsheds.** Negative public opinion regarding solar sites on agricultural lands or scenic views could potentially be avoided by using VTrans properties or highway right-of-way sites that meet practical site considerations.

VTrans designed the following process for developing and implementing solar photovoltaic projects (*6*):

- **Step 1—Assemble project team.** Review the core capabilities and competencies required for successful project development, and secure commitments from internal and external partners who can provide this expertise as the program progresses.
- **Step 2—Evaluate candidate.** Provide direction on how to evaluate candidate project sites and assist in determining go/no-go early to rule on fewer sites for further consideration.
- **Step 3—Evaluate financial analysis and ownership model.** Evaluate project aspects that could direct the project to one business model or another. Establish rough financial potential for all parties involved. If VTrans is procuring through a design-build (DB) or an engineer, procure, and construct (EPC) method, release of the request for qualifications or request for proposal must occur in parallel. If VTrans is procuring through a traditional design-bid-build method, final design and permitting need to occur in advance of procurement.
- **Step 4—Perform due diligence and project confirmation.** Evaluate each of the components of the feasibility study in more depth, including a more in-depth financial review (i.e., pro forma tool).
- **Step 5—Implement project.** If the contract is DB or EPC, this step includes an in-depth discussion of the issues with the contractors and quality control on assumptions, leading to a recalculation of the financial performance of the projects from both parties and a final negotiation of agreement terms. Construction and commissioning follow negotiations.

PLANNED DOT SOLAR DEPLOYMENTS IN THE RIGHT-OF-WAY

Several state DOTs are planning to implement solar energy projects in right-of-way sites. Details of the efforts for these states are provided below.

Arizona DOT

Arizona DOT is moving toward implementing larger solar projects. Its current solar implementation involves small panels to power specific devices, such as street lamps and weigh-in-motion systems (*39*). Future solar projects in consideration may include right-of-way installation as well as installations on noise barriers (*39*). Potential sites have not been formally identified, but Arizona has a high solar potential and many highways with a substantial right-of-way width that could be considered for a solar project (*39*).

Delaware DOT

Delaware DOT does not have any specific plans to install solar sites in the right-of-way, but the DOT is interested in solar energy as a way to meet renewable energy goals as well as help with operating costs (*23*). The DOT has proposed revising the legal structure to accommodate solar and other renewable energy transmission projects in the right-of-way (*23*).

The Delaware Transit Corporation has retrofit facilities with photovoltaic solar panels to generate cost savings through reductions of fossil fuel energy use. The solar-generated power is being used for lighting, computers, air conditioning, and other daily electric loads of the buildings. The project was bid in 2010 and completed in 2012 (*48*).

In general, solar installations in Delaware are increasing because the state set a target of achieving 25 percent of its power from renewable sources by 2026, with 3.5 percent required to come from solar power (*49*).

Florida DOT

Florida DOT recently sponsored two research projects related to solar facilities in the right-of-way. The first project looked at value extraction from highway right-of-way and provided a screening tool for feasibility of solar energy application in highway right-of-way sites. The second provided a detailed analysis of a solar photovoltaic system installed by the Florida Turnpike Enterprise at a service plaza and relevant best practices for future installations (*50*).

Currently, solar right-of-way projects in Florida are not at the stage of widespread adoption because they cannot generate required revenues and profits to make projects viable for all stakeholders (*50*). Although solar energy in the right-of-way might not be an income generator or cost-reduction option for Florida DOT at this moment, market and policy forces might change over time. Grid parity, or the ability of solar power to generate electricity at the same level cost as other energy sources, will fundamentally change the decision on whether to install solar facilities or not. This dynamic set of forces will surely change in the coming years due in large part to decreasing solar prices (*50*).

Georgia DOT

Georgia DOT, in collaboration with private partners and utility companies, developed a solar array in an interstate right-of-way. The solar array area is known as "The Ray." The solar array is made up of 2,600 high-efficiency panels and is expected to have a capacity of 946 kW to DC or

800 kW to AC. Georgia DOT licensed the use of the property to Georgia Power for 35 years. Installation of the solar array is expected to be completed in early 2020 (*51*, *52*, *53*).

In a related project, Georgia DOT partnered with an international infrastructure company to test drive-over solar panels. Fifty square meters (about 538 sq ft) of solar paving were installed at the Georgia Visitor Information Center near the Georgia–Alabama state line. The photovoltaic pavers used in the installation can be applied directly over existing pavement, which eliminates the need to rebuild or build new road infrastructure (*54*).

New Mexico DOT

New Mexico DOT conducted a research project to identify best practices and determine the financial feasibility of generating solar power on DOT property at the lowest cost. Part of the study included a financial feasibility analysis, and researchers found that solar energy generation within New Mexico DOT's surplus right-of-way is cost effective at select districts and utility territories. The research created a guide that provides a process to develop a solar photovoltaic project at New Mexico DOT and includes the following steps (*7*):

1. **Establish project team and management.** Communicate between management and district personnel for intent to develop solar projects and establish a breakdown of responsibilities.
2. **Assemble project team.** Review needed staff and associated responsibilities.
3. **Conduct preliminary site assessment and evaluation.** Determine the project category, such as small properties for facility-level systems that will offset demand, and larger or surplus properties to serve non-DOT load.
4. **Determine appropriate model and partnership.** Review potential contracting pathways such as partnering with a developer to bid on a utility RFP or contract for generation, releasing an RFP to identify interested third-party developers, directly communicating with third-party developers to determine interest, and completing necessary steps to develop an energy services performance contract.
5. **Perform due diligence of priority sites.** Conduct necessary due diligence once a partnership is agreed upon.
6. **Conduct project development and maintenance.** Provide final design, construction, long-term maintenance, and transfer of ownership.

Maryland DOT

In 2018, Maryland DOT announced plans to install solar power on up to 35 DOT sites, including buildings and parking lots. Maryland DOT selected six master contractors to compete to provide solar power at the facilities. Maryland DOT plans to license land to the developer, who will construct, own, operate, and maintain the renewable energy infrastructure. The DOT will buy power at a fixed rate for 20 to 25 years and expects electricity cost savings of 30 to

40 percent. The program is expected to create 298 construction and 28 operations and maintenance jobs. The 35 sites will generate 46,000 MWh per year, which is approximately 12 percent of Maryland DOT's annual electricity usage. Maryland DOT is planning for a second phase of the program to begin shortly after implementing the initial 35 sites. The second phase may include solar projects at airports, ports, and transit-oriented developments; on noise barriers; and on unimproved land (*38*).

Maryland DOT reported a few obstacles when implementing its solar program, including electrical grid connection issues, lack of space for the project, and competing uses (*20*, *39*). Some of the issues with lack of space and competing uses are related to state law. Maryland has a law that is used to promote the planting of trees on unimproved land in an effort to improve the quality of water in Chesapeake Bay (*20*, *23*). To overcome these limitations, and due to restrictions on removing trees, Maryland DOT considered planting prairie grass underneath the solar panels to offset the impact from tree removal (*20*).

Michigan DOT

Michigan DOT has installed solar canopies and is interested in implementing solar facilities on a larger scale. The DOT's interest in solar energy is partially due to a state mandate to use renewable energy. Currently, Michigan does not have any solar installations in right-of-way. One issue the DOT is facing is related to budgeting, which makes it difficult for the DOT to fund positions to support the development of renewable energy at the department. Michigan DOT is also concerned with issues related to tying solar installations into the electrical grid (*21*).

Michigan DOT developed a solar canopy mounted above a carpool lot at the interchange of an interstate and state highway. The canopy is comprised of 385 panels that provide shade and cover for 45 parking spaces. The solar array generates 106,000 kWh annually, or approximately $13,500 annually via net metering credits. The electricity is used to power lighting for the parking spaces and the interchange. Michigan DOT partnered with private companies to design and construct the project and coordinated with the local utility company to connect the canopy to the grid. Michigan DOT is the owner of the solar installation.

The solar project was funded by a grant from the U.S. Department of Energy. The panels have a 25-year warranty, and the other system components have a 10-year warranty. The utility was reluctant to approve the project for net metering because the project was designed to be larger than what the parking spaces and interchange need for electricity. The utility requested that Michigan DOT reduce the size of the project in half. Michigan DOT worked with the utility to gain approval and was required to join the system to two meters (*8*).

In addition to the canopy project, Michigan DOT installed solar arrays at three rest stops in 2011. Michigan DOT intends to continue increasing the renewable energy capacity of rights-of-way, but Michigan DOT staff noted that new projects lack internal support to develop another solar facility in a right-of-way project since it is difficult for Michigan DOT to reallocate funding from other needed projects. Installing solar facilities also requires an upfront investment that can be difficult to justify when there are competing pressing needs in the local community (*8*).

Minnesota DOT

Minnesota DOT is exploring how solar energy development in the right-of-way can help meet energy needs, reduce long-term operational costs, and reduce greenhouse gas emissions. A Minnesota executive order directed state agencies to reduce greenhouse gas emissions 30 percent from 2005 levels by 2025, and facility energy use 30 percent from 2017 levels by 2027. To help achieve these goals, Minnesota DOT has a number of solar projects (*55*).

In 2019, Minnesota DOT completed a project to install solar panels on the top floor of a parking garage owned by the DOT and operated by the City of Minneapolis. The solar garden includes 3,760 panels and is expected to produce 1.4 MWh of electricity each year. The solar panels function as a carport above parked cars on the top floor of the parking structure. Minnesota DOT executed two 25-year agreements with energy companies to purchase 7.4 million kWh annually from community solar gardens located throughout the state. This is equivalent to 24 percent of Minnesota DOT's annual electricity use (*55*).

Minnesota DOT has installed solar projects at several sites, including visitor centers and a district headquarters building. In addition, Minnesota DOT is pursuing projects to install solar facilities on DOT property and use the energy produced to offset its energy costs. Minnesota DOT did not move forward with some projects due to concerns about cost effectiveness and uncertain payback periods (*56*).

Texas DOT

In 2012, Texas DOT conducted a research study evaluating potential uses to extract value from its land holdings (*57*). Part of the study evaluated the feasibility for installing solar power systems on Texas DOT lands. At the time, the main barriers to implementation of solar panels were cost and long payback periods. The study noted that as demand for solar panels increases, prices will fall. The study evaluated the feasibility of solar panel installations for various concerns, including technical, political, legal, financial/economic, environmental, social impact, and safety (*57*).

Texas DOT is planning a right-of-way solar project adjacent to an airport at the intersection of two state highways (*20*). Texas DOT also negotiated a new contract at a historically low rate (i.e., $0.03/kWh for electricity, not including transmission charges) for 100 percent renewable energy. This contract resulted in Texas DOT saving $5 million in the first year. In 2017, a new statewide contract was implemented that includes opportunities for PPAs for wholesale renewable energy, coordination of on-site solar power with energy contracts, and financial incentives for conserving energy during times of peak demand. With the new electricity procurement contract in place, Texas DOT can more easily pursue right-of-way renewable energy opportunities (*20*).

Utah DOT

Utah DOT began to explore installing solar energy in the right-of-way as part of a Transportation Research Board–implemented project that started in 2017. Utah DOT issued an RFI and received six responses in support of installing renewable energy on DOT right-of-way.

Utah DOT determined that funds could be saved through a PPA. Utah DOT is currently moving forward with developing the required planning document and an RFP (*58*, *59*). Utah DOT has identified several potential solar projects, including high-visibility sites (*60*).

Utah DOT installed a solar photovoltaic system on carports in 2017. Phase 1 generated 93 kW, with a total project cost of $215,000, while Phase 2 is expected to generate 270 kW at a cost of $371,000. Utah DOT will use a PPA for Phase 2 to reduce or eliminate maintenance costs and improve site selection. Utah DOT learned several lessons from this project, including the following (*7*):

- Consider interconnection capabilities and transmission line capacity within corridors for candidate solar sites.
- Have an internal site approval process that includes impacted DOT departments.
- Identify success metrics early to measure success of projects.
- Give developers flexibility in identifying potential solar locations in addition to identifying desired DOT locations.
- Expect a procurement learning process to initiate PPA projects for solar development.
- Ensure flexibility in the solar site location for future highway expansion.

Virginia DOT

Virginia DOT conducted a screening process to assess the suitability of delivering solar energy projects as a public-private partnership and decided that the project should advance to the development phase (*61*). Virginia DOT also held a workshop for the solar energy development project. The purpose of the workshop was to identify and assess risks, probabilities, impacts, and potential mitigation strategies. Virginia DOT evaluated many different sites, including facilities, primary/secondary right-of-way, and interstate right-of-way. The workshop was productive and began to formalize risk discussions. More robust workshops and a quantitative risk analysis are expected as the project progresses with a more defined scope (*37*).

DOTs Interested in Implementing Solar in the Right-of-Way

In addition to the states that have implemented solar projects or are working toward solar projects, several states have expressed interest in such projects. These states are in the early stages of evaluating the potential for solar installations or have expressed general interest in solar projects, as summarized below.

California DOT

Caltrans has installed 70 solar facilities under the Clean Renewable Energy Bonds program (CREBs) and is interested in installing solar facilities in the right-of-way (*9*). CREBs, which was part of the Tax Incentives Act of 1995, is an incentive program used to encourage alternative energy sources and energy conservation. Caltrans originally had 93 applications approved under the CREBS program but after some reevaluations and scope changes, the number of projects was reduced to the 70 installed facilities (*9*).

All 70 solar projects were completed and went online in 2013 (*9*). Solar projects included eight different type of facilities, ranging from maintenance and equipment shops, laboratories and office buildings, to toll bridge and truck inspection facilities (*9*). Most solar installations were completed on maintenance facilities, with less than ten installations for each of the other facility types.

The solar installations have helped Caltrans meet the Governor's Zero Net Energy executive order that set a goal toward achieving zero net energy for 50 percent of the square footage of existing state-owned buildings by 2025 (*62***Error! Reference source not found.**). Solar facilities have been installed in all 12 Caltrans Districts and have the capacity to generate 2.4 MW of power. Caltrans estimates that the electricity produced from CREBs solar installations could power 500 homes annually (*9*).

Monitoring of the solar installations has been an issue for Caltrans, which led Caltrans to start contracting out the remote monitoring of the solar installations (*9*). Caltrans also contracts out maintenance for the solar installations (*9*).

Colorado DOT

In 2010, Colorado DOT began exploring energy generation capabilities within its right-of-way sites to power rest areas, maintenance facilities, and intersection lighting and signaling. The goals of the project included the following (*2*):

- Identify energy resources in the right-of-way that are high in quantity and quality and will result in reduced operation costs.
- Conceptualize and identify potential energy cost saving measures using alternative energy generation that will reduce Colorado DOT energy costs.
- Evaluate the physical and operational potential of using right-of-way areas to generate and sell energy to electric utility companies.
- Implement cost-effective alternative energy sources statewide to save financial resources and reduce indirect greenhouse gas emissions.

Colorado DOT conducted a research project in 2015 to identify potential impacts of solar arrays on highway environment, safety, and operations (*63*). The research looked at case studies from projects in other states and in other countries. The study recommended that Colorado DOT explore the use of its right-of-way for solar energy development, which can provide financial revenue by leasing land to energy providers. The electricity generated can be placed on the electrical grid and/or reduce costs to the DOT by powering its assets with the solar-generated electricity (*63*).

Connecticut DOT

Connecticut DOT installed solar panels at two rest areas in 2011 and 2012 (*64*). In 2016, Connecticut's Transportation Finance Panel reported to the governor that the state should look at selling or leasing highway right-of-way for renewable energy generation and development as a way to increase Connecticut's clean renewable energy production (*65*).

New York DOT

New York DOT is considering solar installations along interstates and rest areas (*2*). New York DOT is still early in the process of selecting a developer and final sites. To support the process to date, New York DOT staff prepared an informational packet that addressed all concerns and requirements identified by FHWA in its guidance documents and related federal regulations. This informational packet was used during discussions between the New York DOT commissioner and the FHWA division administrator. New York DOT noted the importance of having a mandate for renewable energy from the governor during these discussions (*6*).

New Jersey DOT

New Jersey DOT is assessing the possibilities for constructing solar light poles and photovoltaic arrays at its rest areas. In addition, New Jersey DOT is retrofitting over 200,000 utility poles with solar panels (*2*). New Jersey DOT has contemplated the use of solar energy along a corridor and charging fees for utility use within the corridor. The lease of right-of-way for solar power did not proceed due to safety concerns, legal issues, and lack of statutory authority (*16*).

Washington DOT

Washington State DOT is considering potential solar installations along interstate highways (*2*, *47*). However, no detailed plans, sites, or specifications about installations have currently been published.

SUMMARY AND DISCUSSION

The literature review included research reports, Caltrans documents, guidebooks from other DOTs, federal guidance documents, AASHTO references and surveys, and project reports resulting from the implementation of utility-grade solar generation sites. The literature review found that many DOTs have engaged in the development and implementation of solar facilities in rights of way. Many of these activities are aligned with state rules for the development of a renewable energy portfolio. A majority of DOTs engaged in developing solar installations in rights of way are focused on the installation of smaller-scale solar facilities that are designed to meet the electric needs of a particular DOT asset or facility. For example, Ohio DOT installed a solar array to offset the energy consumption of a nearby bridge, and several other DOTs are planning to install solar arrays to provide energy for rest areas, maintenance facilities, or electronic traffic devices at intersections.

Few DOTs have implemented solar projects that are intended to produce power beyond the electric need at the location of the solar site, which relates to the fact that DOTs often work with electric utilities using net metering agreements that are designed for small-scale production of electricity that approximately matches the electricity used at the site. As a result, only a little, if any, electricity that is generated at the site is sent to the grid for use by other electricity customers.

Large-scale or utility-grade solar installations have been developed in Massachusetts and Oregon. In both cases, the DOT entered into a PPA with a developer that provides financing that absorbs most of the cost to develop the site. The developer sells the energy generated at the site back to the DOT at a fixed rate that is either equal to or slightly lower than the local utility's retail rate.

The benefits of PPAs result from federal and state incentives and vary based on statutory rules that define state credits for taxes and carbon offsets. Simplified, the DOT provides state property for development, has little upfront cost, and in return gets credit for meeting state renewable energy portfolio requirements and receives a fixed energy rate for the duration of the agreement. The developer provides financing, design, and construction expertise; maintains and operates the facility; and in return receives the income from the energy sales as well as any tax credits and other local incentives. The local electric utility provides access to its electric grid and in return usually receives a grid access fee and can use the solar energy to offset carbon emissions from coal-fired plants.

States with experience developing utility-grade solar facilities have provided detailed accounts of best practices toward successful project development. Best practices include developing an understanding of the benefits available to solar project stakeholders, developing public outreach and being aware of potential concerns by local landowners, developing an effective methodology to screen for potential project sites, understanding the benefits of various partnership models for project procurement, and understanding the needs for solar facility operation and maintenance.

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APPENDIX B: FOLLOW-UP INTERVIEW SUMMARY

Caltrans Project No. P1253
Caltrans Task No. 3177

Solar Power Initiative Using Caltrans Right-of-Way—Follow-Up Interview Summary

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DISCLAIMER

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INTRODUCTION

This document provides a summary of interviews the research team conducted in the spring of 2020 with a selection of states that have implemented utility-scale solar facilities. The purpose of the interviews was to acquire insight into best practices and lessons learned from utility-scale solar installations in the state right-of-way that were not available in the literature. To that end, the research team developed a questionnaire with 32 interview questions (see the Appendix).

In accordance with a request from the California Department of Transportation (Caltrans), the research team targeted state department of transportation (DOT) and tolling authority personnel from nine states: Colorado, Florida, Hawaii, Maryland, Massachusetts, New York, Ohio, Oregon, and Vermont. The research team was able to schedule interviews with seven states; Hawaii and New York were unable to participate. In many cases, project managers for the solar projects of interest were no longer with the DOT or tolling authority, so interviewed staff were not always able to provide responses for all areas of interest described in the questionnaire.

RECOMMENDATIONS AND LESSONS LEARNED

This section presents a summary of the recommendations and lessons learned offered by the interviewees. A full summary of each interview with state officials is provided in the following section. The research team arranged recommendations and lessons learned into four categories: (a) solar program recommendations, which apply to an agency's entire solar program that encompasses the development and supervision of many solar projects; (b) planning phase recommendations, which apply to the early stage of solar project planning; (c) development phase recommendations, which apply to the development of a specific solar project; and (d) operation and maintenance recommendations, which apply to specific solar projects once installation is complete.

Solar Program Recommendations

The following are recommendations provided by state officials that apply to an overall state program for the development of solar projects in the state right-of-way, including recommendations to start a state solar program.

- **Assess the Solar Project Financial Viability.** Solar projects described by DOTs fell into two categories: solar projects driven largely by a need to meet renewable energy goals, and solar projects focused on evaluating solar viability. Projects focused on renewable energy goals were often required to be economically viable as well; as such, solar projects were positioned as a "win-win," both reducing DOTs' carbon footprint and at the same time saving DOT funds. In several cases, by using a power purchase agreement (PPA) or similar legal instrument, DOTs were able to implement solar projects with no or little financial investment. One DOT noted that an additional benefit was an improvement of the agency's environmental, social, and governance rating without negatively affecting the agency's finances. Solar projects evaluating the viability of solar technology were usually financed by grants, which provided additional flexibility since economic viability was not a project requirement.

- **Align DOT and State Administration Goals.** One DOT (Oregon) stated that the key to the success of a solar project is for the DOT administration and state-level policies to be aligned and working toward the same goals. For example, a self-sufficient energy policy can create an incentive for solar energy projects.

- **Consider the Definition of Solar Facilities as a Utility**. Inclusion of solar facilities in the DOT's utility accommodation policy can facilitate the implementation of solar projects in the state right-of-way. Inclusion of solar facilities in the DOT's accommodation policy usually allows the DOT to implement solar projects without the need to get Federal Highway Administration (FHWA) approval for each project through a right-of-way use agreement. Several DOTs started updating their utility accommodation policy before finalizing their solar program, and some are still in the process of finalizing the changes.

- **Formalize the Solar Program.** DOTs stated that a formal rather than a limited or ad hoc solar program has several benefits. For example, it provides a mechanism to transition expertise when DOT staff turn over or retire. A formal solar program can further help to include solar activities in the DOT's long-range strategic or sustainability plan.

- **Consider Initial Project Effects on Solar Program Momentum.** Several DOTs noted that issues with the initial solar project made the DOT question the feasibility of solar projects in general and somewhat stalled the momentum of the solar program. Although issues should be expected with a DOT's initial solar project, it is important to be aware that significant problems can have a far-reaching effect on the viability of the DOT's solar program.

Solar Project Planning Phase Recommendations

The following are recommendations provided by state officials that apply to the early planning phase of one or more solar projects in the state right-of-way.

- **Estimate Solar Panel Maintenance Costs.** DOTs reported that for the most part, solar panels required little maintenance. However, some DOTs reported that maintenance costs, such as the costs for mowing and cleaning, were initially underestimated. Projects that have only a financial benefit can result in a negative net benefit if maintenance costs are underestimated. One DOT that owns the solar panels reported that maintenance of the panels is difficult because the site is unique to the DOT, and spare parts are not readily available. Having a company with solar site experience to support and maintain the site if something goes wrong is critical.

- **Evaluate Renewable Energy Incentive Programs.** Renewable energy incentive programs can be important in making solar projects economically viable. Incentives at both federal and state levels are decreasing, which makes building new non-utility-scale solar projects challenging. Keeping track of incentive programs is essential since they might change over time, which could have a significant impact on the financial viability of solar projects.

- **Ensure a Diverse Solar Project Team Composition.** All agencies interviewed commented on the composition of successful solar project teams. It most cases, it was beneficial to include members from several agency departments, such as right-of-way, mapping, contracting, maintenance, and administration. The project should further include staff with a legal background to draft legal documents and agreements. Several DOTs involved university researchers to provide basic information to get solar projects started or to provide subject matter expertise during solar project development. One DOT (Florida) stated that some of the solar project issues could have been averted by keeping university researchers on call for the duration of the solar project implementation. Several DOTs stated that they underestimated the time commitments and expertise required of solar projects. Solar project development and implementation take significant effort and cannot be accomplished on a part-time basis. DOTs suggested establishing the position of a program manager and program assistant to ensure the success of the solar program.

- **Consider the Combination of Solar Projects with Electric Vehicle Infrastructure.** One DOT (Maryland DOT [MDOT]) is having issues with the installation of solar and electric vehicle infrastructure together because they are different projects with separate funding sources. Structuring MDOT's master solar contract to incorporate electric vehicle infrastructure would have been preferable. Because this was not feasible, MDOT currently asks the solar developer to make the solar installation *electric vehicle ready* but leave the actual electric vehicle installation to a second contractor. Electric vehicle ready essentially means the solar developer installs an additional conduit and concrete pads so that electric vehicle chargers can be easily installed at a later date.

Solar Project Development Phase Recommendations

The following are recommendations provided by state officials that apply to the development and implementation of solar projects in the right-of-way.

- **Evaluate Contractual Options.** A solar project needs contracting and procurement flexibility. DOTs might be focused on the best value for a state, which does not necessarily mean the lowest project cost. For example, a DOT might include language to use local contractors, companies that create jobs in its state, and solar panels produced in its state. PPAs can be useful contractual tools. The utility should be involved in the development of the PPA and ideally take the lead for most of the project details. Moreover, DOTs advised being cautious about a solar project until there is buy-in from the utility.

- **Consider Master Solar Contracts.** DOTs reported that master solar contracts simplify the implementation of solar projects. However, these contracts can be difficult to develop because, depending on the DOT's structure, they might have to serve more than one agency or division. Building flexibility into the master contract is advantageous because sites and project details may vary greatly from one project to the next.

- **Define Clear Responsibilities**. If the contract with the developer includes responsibility for any needed repairs, the developer will take care of these without need for negotiations with the DOT. If there is a failure and it is unclear who is responsible for repairs, the DOT may end up paying for repairs that were not in the DOT's original budget and may experience loss of electricity generation while the liability question is sorted out by the lawyers.

- **Develop a Process for Solar Site Identification.** Several DOTs developed a project siting process that involved a review by most or all DOT divisions, although at the cost of lengthened site review. DOTs recommended performing a comprehensive and systematic analysis of all DOT surplus properties. Tools such as a geographical information system (GIS) can be very useful if property information is available in a spatial database. Once a site has been selected, there should be outreach to members of the community and nearby neighborhoods to address any concerns they might have. In addition, the environmental analysis for potential sites can be expensive, so it is important to prescreen sites that have a high probability of low environmental impact.

- **Evaluate Local Grid Interconnection.** DOTs should consider the required process, time, and costs for interconnecting a distributed generation unit to the grid. Utility companies typically have a formal process to evaluate interconnection feasibility. Utility companies usually conduct an engineering analysis by request and generate reports specifying the required grid protections, upgrades, and corresponding costs to be borne by the customer. This effort may take additional time and incur significant costs. An entity interested in large solar installations should begin discussions with utility companies early, especially if projects need to be aligned with incentives and are in an area where the grid network may need upgrades to accept solar power. If a DOT partners with a solar developer, the developer should coordinate with utility companies during project conceptual design to discuss individual site conditions for interconnection and the implications for overall project costs.

- **Develop a Process for Public Involvement.** It is important to engage local towns and communities where solar installations are going to be located and to allow for additional time since town review and approval may be required for a project.

- **Evaluate the Expertise and Track Record of Solar Contractors.** DOTs mentioned that contractors or subcontractors involved in the solar project construction did not have sufficient experience. In hindsight, having a contract requirement stating a certain level of experience with solar installations would have been preferable. A careful analysis of customer satisfaction with systems the contractor installed in previous years would have been likely to identify not only the level of experience but also the contractor's attention to quality control and continuous improvement, which are both critical for solar systems. In addition, it is beneficial to have a project team member with sufficient expertise to provide a level of oversight to the contractor during construction.

- **Evaluate the Viability of Solar Equipment Companies.** In some cases, the company selected for a solar project either went out of business or stopped producing replacement parts after a short period, which made it impossible to repair the system. Although it is difficult to predict the solvency of solar equipment companies, there should be some type of review of the company or other type of assurance that the company will support its technology in the future. Ideally, the solar panels that are used for a site should be able to be maintained or repaired by several companies and should not be specific to just one vendor.

Solar Project Operation and Maintenance Recommendations

The following are recommendations provided by state officials that apply to the operation and maintenance of solar projects once they have been constructed.

- **Link the System Performance to the Operations and Maintenance Contract**. If the organization responsible for operations and maintenance benefits financially from the electricity generated by the system, that organization will ensure that the monitoring is consistent and fix problems quickly to maximize its income.

- **Have a Clear Plan for System Monitoring**. DOTs that were not consistently monitoring the output of their solar systems sometimes found that the systems had ceased functioning for months before the problem was discovered. Ideally, the monitoring process generates an alarm, perhaps in the form of an email to several people, when the system develops a problem. Several people should be contacted because the individual responsible for monitoring the status of the system may forget to check a system that has worked correctly every day for months, may simply get tired of looking at the data, may be on vacation, or may have left the department.

Interviews with State DOTs

The following sections provide a summary of each interview that the research team conducted with state DOT officials. Where feasible, researchers organized the information gathered from the interview process using the following structure:

- General Lessons Learned.

- Project Development and Contracting.

- Electricity Generation and Storage.

- Operation and Maintenance.

- Plans and Opportunities.

Interviews were conducted in the spring of 2020 and reviewed by interviewees to correct potential errors and omissions by the research team.

Colorado DOT

Background

The Northwest Parkway is a public toll road located north of Denver, Colorado. The toll road is privately operated by Northwest Parkway LLC (Northwest Parkway), a concessionaire who operates the toll road for the Northwest Parkway Public Highway Authority. Northwest Parkway has a 99-year concession and lease agreement with the Northwest Parkway Public Highway Authority for the operation and maintenance of the toll road. Northwest Parkway has seven solar installations that are producing electricity. A representative of Northwest Parkway was available to respond to the questions of the research team.

General Lessons Learned

To a large degree, the solar installations were driven by economic benefits. Northwest Parkway determined that an opportunity existed to produce sustainable electricity with no financial investment. The solar installations help Northwest Parkway be more sustainable and environmentally friendly.

The solar project's focus was sustainability and economic benefit. Northwest Parkway's board was supportive of the solar project, in part because the project helped the company's environmental, social, and governance rating without negatively affecting the company's finances.

The arrangement in which the developer was responsible for maintenance and was paid for the electricity delivered resulted in a hassle-free implementation that performed to design specifications.

Project Development and Contracting

At the time of project development, two separate utility companies provided electricity to the toll road. One of the utility companies, Xcel Energy, provided solar incentives. To take advantage of these incentives, a solar energy developer, Soltura Energy Capital, approached Northwest Parkway about potential solar projects. After some discussions, the developer and Northwest Parkway signed a 20-year PPA in 2010. Using the available incentives, Northwest Parkway was able to take advantage of the solar installations with no investment cost.

Project stakeholders included Northwest Parkway, Xcel Energy, and Soltura Energy Capital; state agencies were not directly involved. Northwest Parkway's legal counsel reviewed and approved the PPA, which defined that the developer was responsible for the design and construction of the solar installations.

The right-of-way approval process did not encounter any difficulties. As the concessionaire, Northwest Parkway approved all necessary right-of-way permits.

The public was not actively involved in the solar project development process. Northwest Parkway's impression was that the public was supportive of the solar project because it produces clean energy and helps offset costs. The solar installation was not actively publicized, but an informative brochure was created and made available online.

Northwest Parkway did not see a need for a solar project manager during project development since the project development process was very streamlined. Maintenance and any other issues that could emerge with the installation are the responsibility of the developer.

Electricity Generation and Storage

The solar installations were scheduled to be completed by June 2011. The developer was able to complete the installations early and start production tests in May of 2011. From June 2011 to December 2019, Northwest Parkway saved $26,262 in electricity costs. Northwest Parkway was further able to reduce its energy consumption by over 50 percent, from 1.3 MWh in 2008 to 0.6 MWh in 2019.

In general, the solar installations are generating the expected amount of electricity. The system was not overdesigned to account for dirt and grime buildup, and grime buildup apparently did not significantly affect the site's electricity production. In fact, there was only a 1.3 percent drop in electricity generation between 2012 and 2019 (99,462 kWh for 2012 and 98,140 kWh for 2019).

No electricity storage is associated with the installations. All installations are connected to the grid and take advantage of net metering. All energy produced is being used, and Northwest Parkway does not have any issues with producing too much power or having too few users of the electricity.

The cost of electricity produced from the solar installations is lower than the cost from the utility company. However, the PPA includes a fixed escalation rate of 3.5 percent per year. As a result, the two rates have been converging over time since the electric company's rate has not increased.

Operation and Maintenance

The developer is responsible for maintenance of the solar installations except for mowing. Northwest Parkway mows the solar sites along with its regular mowing duties, normally two to three times a year. During construction, the developer was required to restore the site's landscaping to its previous condition.

The developer remotely monitors the solar installations and provides Northwest Parkway with monthly reports. A few minor technical issues occurred with the installations, but they were handled by the developer. The PPA is structured such that the developer only gets paid for electricity produced, which is an incentive to ensure that the system remains operable.

No issues with settling or erosion of the solar sites and no instances of the solar installation being used for shelter have occurred. The installations are fully fenced, and no issues have transpired regarding vandalism or theft.

Plans and Opportunities

The PPA has a duration of 20 years. Once the PPA ends, the solar installations become the property of Northwest Parkway, which will allow Northwest Parkway to use the electricity produced as long as the installations are properly maintained. The PPA includes a buyout option if Northwest Parkway decides to end the agreement prematurely.

Plans exist to install two electronic message signs that will include local solar power and a small battery unit for storage. Northwest Parkway has been upgrading its lighting and signs to reduce overall electricity consumption. The company has been replacing lights with LEDs and signs with highly reflective signs to eliminate the need for illumination.

Currently, no plans exist to expand the solar program. Northwest Parkway is open to installing more sites as long as the projects have an economic benefit, which will likely be based on the availability of incentives.

Florida DOT

Background

The Turkey Lake Service Plaza solar research project, or Sun Plaza project, started in 2009 as a joint project involving the Florida Turnpike Enterprise (FTE), Florida DOT (FDOT), University of Florida, and Duke Energy. The 112-kW system was completed in 2012 using an array of 468 fixed solar panels (*1*).

General Lessons Learned

Overall, representatives from FTE and FDOT offered the following lessons learned:

- The University of Florida provided very good information and research to get the project started. Unfortunately, it was not involved in subsequent steps. It would have been better to have its expertise on call for the duration of construction and implementation.

- The solar project team had several transportation experts who were not necessarily solar experts. The solar project would have greatly benefited from a solar expert on the team, such as staff from the university.

- The company that produced the selected solar panels and inverters stopped producing replacement parts after a few years, which made it impossible to repair the system once it started experiencing equipment failures.

- A few things went wrong on the project, which made FTE question the feasibility and stalled the momentum of the solar program in general.
- The solar installation did not include a system to notify FTE about power generation failures. This resulted in the system being shut down for about two months without FTE noticing the blackout.
- Due to several unfortunate events early on in the project, in addition to ongoing routine maintenance costs that were higher than expected, the solar system was not a profitable investment overall. However, the project provided the department with valuable information through lessons learned throughout the project.

Project Development and Contracting

The Florida solar project started with a discussion about how Florida's Turnpike could reduce its carbon footprint. Someone suggested placing solar panels on noise walls. Based on the discussion, FTE teamed with FDOT and started a project in 2009 to research cost and opportunities to improve energy conservation and reduce greenhouse gases, which involved several contractors including the University of Florida. The research project involved a review of several potential green energy sources, including solar energy; exploration of innovative financing strategies; and formulation of marketing and educational ideas (*2*). The research effort was successful because it had the full support of the FTE and FDOT leadership team.

Based on the research study, FTE created a development plan with the purpose of transforming the Turkey Lake Service Plaza into "Sun Plaza, A Solar Destination." The intent was to have a location that would not only generate solar electricity but would further showcase different types of solar electricity generation technology and educate the public about options, incentives, and benefits for homeowners. The site was intended to be a prototype for additional solar sites on the turnpike system and statewide in the future.

Project development consisted of two phases: Phase 1 focused on identifying best solar technologies, panel installation options, and plaza design, and Phase 2 focused on the creation of the solar park destination to promote and educate the public on solar technologies that could be used by individuals or businesses.

Preliminary Site Identification

The Turkey Lake Plaza is in the vicinity of Walt Disney World, Universal Studios, and Sea World, and carries tens of thousands of vehicles daily. The site had enough space for the desired number of panels and was about to be demolished and reconstructed. The site included a gas station and convenience store that were in the beginning stages of being rebuilt, providing an ideal location for Phase 1 of the project.

Project Contracting

Following the research project, FTE published a request to negotiate for proposals and then selected a contractor called Solar Source. FTE used the same on-site construction manager overseeing the Service Plaza reconstruction to also oversee the installation of the solar panel system. Unfortunately, the construction site manager did not have much experience installing solar systems. Moreover, the electric company hired by the contractor as a subcontractor also had very little experience. With more experienced oversight, some issues that came up during and after the completion of the project could have been discovered and possibly avoided much earlier.

At the beginning of Phase 1, the installing contractor began installing poles for the racking system and discovered abandoned fuel tanks. FTE renegotiated the contract with Solar Source and developed a plan for the installation of the steel racking system that would avoid the abandoned fuel tanks. The plan involved pouring footers that could be used to span the fuel tanks.

Three months after installation, a strong wind flipped and damaged about 120 panels. A review of the damage found that the contractor failed to install a small locking plate that locks the panels in place and prevents the wind from uplifting the panels. All 120 panels and a portion of the racking system had to be replaced, which was paid for by the contractor. However, by then, FTE owned the system and did not produce any power for three to four months while the replacements were being done.

In other instances, FTE staff was able to provide better oversight. For example, an FTE electrical engineer found that the surge protection was not installed. Once the contractor installed the surge protection, the FTE electrical engineer found that the surge protection in use was not UL rated. Next, the electrical engineer found that the conductors from the surge protection to the electrical box were very long and needed to be shortened. That correction also meant swapping out the surge protection units.

A few months later, the site was hit by lightning, which damaged 60 or 70 panels despite the surge protection. A review found that the solar panels were not properly grounded. The contractor had used an indoor lug instead of an outdoor lug to connect the ground conductor to the panels, and the lug had badly corroded. FTE could not prove that lightning was the cause of the damage, so for about eight months, disagreement ensued regarding the repair costs. FTE finally agreed to split the repair costs 50/50 with the contractor. Eventually, the contractor replaced all the wrong parts and properly grounded all panels.

Originally, use of fencing around the solar panels was not planned. However, FTE found that fencing would be a necessary addition to keep the public away from the solar panel arrays. Ultimately, the cost of the whole system was about $450,000, including the fencing.

Initially, no cover existed over the power inverter. As a result, the inverter aged very quickly. In 2018, an LCD display panel inside the inverter housing malfunctioned, which unfortunately could not be replaced. FTE also had problems with rodents getting into the inverter. Although no damage was caused, FTE was never able to determine how the rodents got inside.

Public Involvement and Concerns

To gather public support, FTE created an informational video that described the purpose and benefits of the solar project to the public. As part of Phase 2, the plan was to have an outreach and educational space for renewable energy and efficient energy technologies. Several companies intended to build showcases for efficient energy technologies in public-private partnerships. For example, the University of Florida was going to donate a small mobile house that showcased translucent walls with insulation, a solar hot water heater system, LED lighting, and other efficient energy systems. In addition, small kiosks that provided additional educational information were supposed to be installed. This part of the project never evolved as planned because a lot of funding for Phase 2 was used to cover repairs during Phase 1.

Electricity Generation and Storage

The owner of the convenience store signed an agreement with FTE to use the electricity from the solar panels for an annual user fee based on power consumption, which resulted in a fee of about $12,000 to $15,000 annually. This agreement was used because the local utility would only pay FTE about a third of the current power market rate if the solar facility was connected directly to the power grid. As a result, it was much more cost effective to size the solar facility to the needs of the convenience store and use all the electricity locally. Overall, the solar system did not pay for itself by the time it was abandoned.

Operation and Maintenance

The project resulted in some unexpected maintenance costs. For example, the ground cover at the site required FTE to mow once or twice a month to keep the solar panels unobstructed. Problems also occurred with bird droppings and residue from diesel and truck emissions. Although the manufacturer claimed the panels were maintenance-free, FTE had to clean the panels about five to six times a year. Mowing the grass and washing the panels cost about $9,000 annually.

At one point, the system shut down, but FTE did not realize it for about two months. The only way to check the system was to use the locally installed telemetry system inside the convenience store or a connected web portal, but no one was assigned the responsibility to check on the generation of electricity.

Due to construction projects such as the I-4 Ultimate project and other road construction changes, large tandem truck drivers cannot easily access the area, and by law, they can only drive for 8 hours and then must rest 16 hours. The space used for the solar installation was identified as a location to better meet the needs for tandem truck parking. FTE looked at the Turkey Lake Plaza and determined that since the inverter was not working and parts were not available, the solar array space could be put to better use as a truck parking facility. Given the cost to reengineer and reinstall the system, FTE decided not to relocate the solar system and simply abandoned it. All solar panels at the Turkey Lake Plaza were removed at the end of January 2020.

Plans and Opportunities

FTE is currently working with local utility companies to install electric, but not necessarily solar-powered, vehicle charging stations at all of its services plazas, creating a corridor of charging stations throughout the state of Florida. FTE continues to investigate innovative ways to reduce the state's carbon footprint, such as the use of small wind turbines to produce energy for local use.

Consideration is also being given to putting more solar panels on FTE-property roofs, but concern exists that the roofs must be replaced in the near future. FTE also found that solar rooftop installations require a transfer switch for the emergency power generators. The idea of installing solar panels on noise walls is no longer a consideration due to concerns about high wind forces such as those that might occur during hurricanes.

Maryland DOT

Background

MDOT installed five solar installations using the state's energy performance contracts. All installations have been successful, are producing electricity, and are owned by MDOT. One solar installation is located on top of a Maryland Transit Administration (MTA) building, two are on top of Maryland Port Administration (MPA) buildings, one is at the Maryland Transportation Authority (MDTA), and one is on a parking canopy at the Baltimore International Airport. These five original installations started the idea for an MDOT solar energy program. In addition to the five solar installations, the Maryland State Highway Administration (SHA) is involved in several small-scale solar projects for localized use of solar-generated electricity, such as mobile signage.

General Lessons Learned

MDOT participated in an FHWA solar peer exchange in 2017. One takeaway was that some states define solar facilities as a utility and include them in the utility accommodation policy. This allows DOTs to move forward with solar projects without the need to get FHWA approval for each project through a right-of-way use agreement. MDOT started updating its utility accommodation policy before finalizing its solar program, but this process has not been completed. Guidance from FHWA was instrumental to the success of the solar program (*3*). Inclusion of solar facilities in the MDOT utility accommodation policy was a key step in making MDOT's solar program successful.

MDOT is having issues getting the solar installations and electric vehicle infrastructure installed together because they are different projects with separate funding sources. Since Maryland has progressive electric vehicle goals, it would have been preferable to structure MDOT's master solar contract to incorporate electric vehicle infrastructure. Because this option was not feasible, MDOT currently asks the solar developer to make the solar installation *electric vehicle ready* but leave the actual electric vehicle installation to a second contractor. Electric vehicle ready essentially means the solar developer installs an additional conduit and concrete pads so that electric vehicle chargers can be easily installed at a later date.

MDOT is the lead agency for several transportation administrations, such as the MPA, MTA, MDTA, SHA, Maryland Aviation Administration, and Maryland Motor Vehicle Administration.

At first, it was difficult getting approval for the master solar contract since the intention was to serve all Maryland transportation administrations. However, as project stakeholders became more familiar with the required process steps, the approval process became less difficult.

Project Development and Contracting

MDOT's goal was to include all transportation administrations in the solar program to ensure a programmatic way of installing solar facilities for the entire DOT. This approach allowed the solar projects to take advantage of all MDOT's resources and coordinate efforts and needs among the transportation administrations. For example, discussions were held about using property from one administration to produce power for another DOT administration.

Solar Project Manager

The solar program's original project manager had little experience with solar implementation when the program started. However, the project manager was passionate about the issues and saw the need for a formal solar program since there was no formal process to implement a solar project.

The solar project manager position was vital to the success of MDOT's solar implementations. The project manager acted as a coordinator whose main role was to oversee solar projects and move all solar projects forward. Some of the characteristics that made the project manager successful included the ability to motivate, pull people together, generate buy-in, and execute. These abilities were useful when it was necessary to convince MDOT leadership about program specifics. In addition to the main solar project manager, other primary project manager roles at the different administrations were filled, either by a single person or a team of people.

Overcoming Institutional Inertia

The solar program team met with the Maryland transportation secretary to highlight the success of the solar projects installed under the state's energy performance contracts. The transportation secretary then requested a feasibility study, which helped define the economic benefit of additional solar projects. The feasibility study showed that solar projects would not cost more than what MDOT was currently paying for electricity, and MDOT would be able to lock in that rate for the duration of the contract. The transportation secretary agreed to support the solar program if it did not interfere with operations or increase the cost for electricity. The next step was to gain approval from the governor's office. The program was ultimately approved based on the estimated economic and social benefits. The program's social benefit is mainly from shade/snow protection provided to customers by the solar canopies in addition to improved public health as a result of decreased air pollution from displacing fossil fuels.

The state treasurer was also very supportive of solar projects and any climate mitigation activities. Part of that support may be due to a change in the way that the credit rating company Moody's evaluates the state's credit worthiness, which now includes climate mitigation activities as a factor (*4*). Without the state treasurer and governor's support, the master solar contract would probably not have been approved since all master contracts have to be approved by the Maryland Board of Public Works, which includes the governor, comptroller, and state treasurer. Having the state treasurer's support made a big difference in getting the support needed to get the solar program established.

After approval, the solar program had to be implemented throughout MDOT. This approval was achieved by finding and recruiting employees who were supportive of the solar program and enlisting their help in spreading support for the program in their respective administrations. The solar program did not experience any active opposition, but some naysayers registered concerns. However, all the leaders in the different MDOT administrations were supportive of the solar program. It was also helpful that the solar program was located at MDOT headquarters, which made it easier to coordinate activities with MDOT leadership.

Coordination with Other State Agencies

The solar team worked with the Maryland Department of General Services (DGS), which is responsible for buying commodities for all state agencies. It was critical to coordinate the solar projects with DGS since there was a possibility that the solar power produced might lead to the state purchasing electricity and not using it. Further, DGS enters into major energy performance contracts for all state agencies, by which a contractor assesses a portfolio or a building complex and finds ways to implement energy efficiency measures. The energy efficiency measures are paid for by the energy savings, so there is no net cost to the state. In addition to DGS, the following agencies were involved with or supported the solar program:

- The Office of Procurement played a significant role and was a core member of the team that set up the initial solar program.
- The Office of Attorney General played a major role in drafting the contract documents.
- The Office of Safety Management and Risk Control is a core team member of the solar program and helped draft bonds and risk management language that was included in the contract documents.
- The Maryland Energy Administration helped review the master solar contract. The administration also helped qualify the six solar contractors currently using the master contract.
- The Office of Planning and Capital Programming helps with the vetting of potential sites because they manage MDOT's long-range and strategic plans.
- The Office of Real Estate is a partner of the solar program and must approve any site the solar program wants to use for a solar project.
- The Office of Finance helps with the review of any existing bonds or leases a potential site may have. Even though the developer is paying for the solar installation, existing bonds may prohibit certain types of uses on the property. MDOT may be able to work around an existing lease at a potential site, but it will make the process more complex.

- The SHA Utility Division has been very helpful in managing the permitting and approval of the use of right-of-way. The Utility Division has also assisted by coordinating internally with all the SHA departments to ensure the proposed sites are fully vetted and reviewed.

- The Office of Planning and Preliminary Engineering is an important part of the team and helped develop and review proposals. The office contracts with a solar expert, located at the MDOT Office of Environment, who is an engineer and helps with the review of information from developers. This assistance is useful since MDOT staff usually do not have the capacity to assist or have the special expertise required to review solar installations.

- MDOT coordinates solar activities with the Maryland Department of Natural Resources Critical Area Commission and has a memorandum of understanding with the commission that allows up to 5,000 square feet (about 0.11 acres) to be disturbed in the critical area for a solar installation without the need for a permit from the commission.

- MDOT coordinates with the Office of Facility Maintenance when a solar project is considering a site on a building.

Public Involvement

MDOT has not conducted formal public outreach or public meetings to publicize the solar program. For individual projects, MDOT plans to follow its standard procedure regarding public outreach, which includes information flyers that are handed out at public events, including conferences and meetings. MDOT also posts information about the solar program on the MDOT website and MDOT's LinkedIn page.

MDOT has received feedback that the public is opposed to solar installations on agricultural land or in ecologically sensitive areas. When discussing solar projects, it is therefore a good practice to mention that the projects will be installed on properties that are already developed or disturbed. The social aspect of the installations seems to resonate with everyone. Other aspects of solar energy that may be good to mention are the health benefits of replacing dirty energy with clean energy, having a reliable energy source, and having a predictable cost associated with using the PPA.

Master Solar Contract

The master solar contract prequalified contractors and established MDOT's solar baseline requirements. Certain items were left out of the contract on purpose. For example, capacity limits are not specified, which was a lesson learned from other DOTs that met capacity limits faster than expected. MDOT wants to be able to use the master contract for the full contract term and not be limited by any specified capacity limits. The master contract also does not state any particular solar technology, which allows MDOT to incorporate new technologies in projects as they are being developed. In addition to solar technologies, these new technologies include electric vehicle charging, micro grids, and battery storage.

The master contract has cooperative language that allows the contract to be used by all state agencies, municipalities, nonprofits, other governments, and instrumentalities of the state. The idea for a master solar contract came from the director of procurement, who also helped craft the master contract language that provides a foundation for the solar program. Six solar firms are currently prequalified in Maryland as master contractors, which makes it easy to create a task or solar installation project from the master contract.

As of February 2020, MDOT has released two tasks from the master contract, one for the transit administration and the other for the toll authority. The toll authority task includes two park-and-ride sites that are currently under construction. The toll authority wanted to work with the solar developer to install the solar panels while it is constructing the park-and-ride facility. The transit administration task originally included six park-and-ride sites but has been reduced to four sites. Many more tasks are under development, but it can be difficult to get sites approved by all stakeholders that have to agree to a proposed site. MDOT is starting with park-and-ride facilities because they appear to be easier to implement than other potential solar projects.

MDOT is open to the idea of electricity storage, especially for emergency use. Some buildings have generators for emergency use, and battery storage may be used to help offset some of the need for emergency generators. However, current solar implementations do not include electricity storage due to its high cost.

Power Purchase Agreements

MDOT does not have many solar energy experts on staff and is not interested in owning more solar facilities. As a result, MDOT aims to allow developers to license the property to reduce the risk to MDOT of using a PPA. Under the agreement, the developer is responsible for funding, installing, operating, maintaining, and decommissioning the solar installations. MDOT receives the benefit of using the power produced by the solar installations or collecting a fee for the use of the land in the event MDOT cannot use the power. MDOT is entering into PPAs for several sites.

Statutorily, MDOT can enter into land agreements of up to 50 years with developers. However, MDOT decided to align the PPAs with MDOT's long-range transportation plans that have a 20-year horizon and standard solar industry practice. As a result, current MDOT PPAs with developers range from 20 to 25 years. At the end of the contract, the developer is required to remove the installation from the property.

Site Selection

Criteria for the selection of potential solar installation sites included the following:

- No planned highway development or redevelopment for a minimum of 20 years.
- Sufficient size after consideration of safety setbacks (typically 30 feet) along roadways.
- No tree removal.
- Proximity to an interconnection point with sufficient capacity.

It can be difficult to find sites on MDOT right-of-way that meet the selection criteria, especially no tree removal and minimum setbacks. Excess land from completed DOT projects is often a good starting point when identifying potential sites. Surplus property might be used for a solar project if the project generates a benefit to MDOT and does not deviate from MDOT's main business of transportation.

Maryland has several laws, including water quality standards, that can make the removal of trees for solar facilities very difficult. Except for a few remote areas, interconnection point proximity is typically not a problem in Maryland. However, in all cases, it is necessary to evaluate if the current interconnection point can handle the increased load. If the interconnection point needs to be upgraded, it might make the solar project nonviable from an economic perspective.

Once a location is selected as a potential solar project site, it needs to go through a vetting process that involves several departments and agencies. This vetting process is difficult and time consuming.

Electricity Generation and Storage

All current systems are connected to a grid, in part due to Maryland's strategic net metering laws. In general, the solar installations are generating the expected amount of electricity. MDOT is interested in local energy storage, but the cost is currently too high to make energy storage a viable option. MDOT cannot pay more for solar energy than what it is currently paying for electricity. In addition, MDOT has not had to deal with grid-wide outages, as seen in other states. Outages occur only occasionally and are typically localized—for example, during local snowstorms.

MDOT does not have any issues with producing too much power or not having enough users. This element may change in the future since Maryland increased its renewable portfolio standard to 50 percent by 2030, including 14.5 percent required for solar energy. In 2020, the governor released a new legislation plan that requires 100 percent clean electricity by 2040, which will increase the demand for electricity generated from solar facilities.

Operation and Maintenance

The existing systems, installed under the state's energy performance contracts, are coming to the end of their contract period. One of the systems was inoperative for a period due to a lack of maintenance. In addition, some of the monitoring systems were out of order. To continue use of the solar systems, MDOT needs to find new maintenance contractors, which can be a challenge because the solar installations are not in the operations and maintenance master contract.

Solar systems installed under the master solar contract will be maintained by the developer for the length of the contract. In addition, the master contract includes a requirement that the developer must install pollinator habitats for ground-mounted installations.

Of the five existing solar installations, only one site experienced a premature failure of a component: the Wi-Fi element of a data acquisition system broke down. The repair involved replacing the part and did not affect the energy-generating capability of the site.

So far, MDOT has not had any issues with vandalism or theft. The systems that are in place are not easily accessible to the public.

Plans and Opportunities

Potential to install solar on additional buildings exists, but some of the roofs are older, and there is concern that the roofs cannot handle the additional weight from a solar installation. However, MDOT anticipates a few roof replacement projects in the next few years. For upcoming roof replacement projects, MDOT has discussed the inclusion of the weight of a solar installation in the roof design with the engineering and maintenance staff.

MDOT is evaluating the installation of solar panels at its Baltimore headquarters and the Hanover complex. MDOT is also looking at an additional 20 park-and-ride facilities along state highways and at Baltimore International Airport. Enough space is available to install approximately 500 kW of additional solar panels to the existing solar system located on the airport's daily parking garage. The airport also has other buildings that could be used for solar installations.

Further, MDOT is evaluating the installation of floating solar panels on top of a stormwater pond at the airport. MDOT would install the panels on floating docks using marine-grade wire for the electrical connections, which might also reduce the number of birds accessing the pond and could reduce the number of bird-related incidents. Similar installations have been completed at a winery in California, in New Jersey, and in Florida (*5*).

MDOT's solar program has been working with the Office of Real Estate to get a list of properties suitable for solar projects. The Office of Real Estate is working on a map of all properties owned by MDOT and will place the information on a GIS layer. The solar program is reviewing the information to identify potential sites for solar installations. Once identified, potential sites will still need to be vetted through the appropriate internal processes.

MDOT is also considering implementing solar panels on noise walls. MDOT is both targeting new noise wall projects and contemplating potentially retrofitting existing noise walls. Solar noise walls could be funded by developers in areas where the community has requested a noise wall, but one has not yet been built.

Massachusetts DOT

Background

Between 2015 and 2018, the Massachusetts DOT (MassDOT) constructed eight commercial-scale solar installations with an aggregated capacity of 4.3 MW. MassDOT's solar installations were built and commissioned under its Solar Photovoltaic Energy Program that made use of the

Massachusetts Solar Renewable Energy Certificates Phase 2 (SREC-II) incentives, which increased financial incentives for solar installations in Massachusetts starting in 2014 (*6*). Interest in the incentive program was greater than the state expected, and as such, solar installation grew rapidly in Massachusetts, and the SREC-II program reached its capacity for new installations in 2016. The state then replaced the SREC program with the Solar Massachusetts Renewable Target (SMART) program in 2018, which provides incentives at a reduced level (*7*).

Under the SREC-II program, the solar market was divided into blocks based on system size, and the blocks were released at different time periods. In addition, the federal solar tax credits must be claimed within three months of a system commissioning. To make full use of all the incentives, MassDOT bundled solar installations into three groups and staggered the construction based on the timing of the incentives and utility interconnection readiness.

General Lessons Learned

MassDOT offered the following recommendations and lessons learned:

- The state incentive programs were important for making solar projects economically viable. The size of the installations and relatively limited solar potential in Massachusetts make incentives an integral part of the decision-making process. Incentives at both the federal and state level are decreasing, which makes it challenging to build new non-utility-scale solar projects.

- Keeping track of incentive programs is essential since they have changed over time, which could have a significant impact on the financial viability of solar projects.

- DOTs should consider the required process, time, and costs for interconnecting a distributed generation unit to the grid. Utility companies typically have a formal process to evaluate interconnection feasibility. Utility companies usually conduct an engineering analysis by request and generate reports specifying the required grid protections, upgrades, and corresponding costs to be borne by the customer. This process may take additional time and incur significant costs. An entity interested in large solar installations should begin discussions with utility companies early, especially if projects need to be aligned with incentives and are in an area where the grid network may need upgrades to accept solar power.

- If a DOT partners with a solar developer, the developer should coordinate with utility companies during the project's conceptual design to discuss individual site conditions for interconnection and the implications for overall project costs.

- Building flexibility into the master license agreement is advantageous because sites and project details may vary greatly from one project to the next.

- It is important to engage local towns and communities where solar installations are going to be located and to allow for additional time since town review and approval may be required for a project.

Project Development and Contracting

The solar project started with a governor-backed initiative called "Leading by Example," which called on state agencies to be energy efficient, use renewable energy, and install renewable energy on state property. The state legislature also established the SREC Carve-Out Program under its Renewable Portfolio System. The SREC program encouraged statewide solar development by offering incentives. MassDOT leadership was supportive of the solar installation effort, in part due to the Leading by Example initiative and in part due to the fact that the solar electricity rate (after the various incentives were applied) was lower than MassDOT's standard electricity rate. The project was focused on being sustainable and green, but the economic benefits were equally important to MassDOT.

Preliminary Site Identification

All MassDOT's key functional areas were involved in the solar site identification process to some degree. State law allows MassDOT to lease excess property for non-transportation purposes as long as it is not needed for transportation purposes in the foreseeable future. To determine whether a property is not needed for transportation and whether it is suitable for proposed non-transportation use, MassDOT has an internal process that is initiated by the MassDOT Real Estate Office. The Real Estate Office identifies a parcel and sends parcel information and the proposed purpose to all relevant DOT sections for review and comment, including traffic engineering, right-of-way, safety, districts (regarding highway maintenance, operation safety, and site access), environmental, and planning (which reviews the long-term plan for the property). By the end of the process, MassDOT determines if the site is potentially suitable for a solar project. Suitable sites are then forwarded to the Highway Division administrator for approval. If the parcel was acquired on a project that used federal funding, MassDOT also sends a request for approval to FHWA.

Project Contracting

MassDOT decided to use the public-private partnership business model and PPA approach to build solar photovoltaic systems. Under this approach, the developer is required to finance, develop, design, construct, commission, operate, and maintain the solar systems. The developer obtains the federal and SREC incentives, while MassDOT purchases all the generated solar power from the developer at the rates specified in the PPA and obtains all net metering credits.

Before MassDOT released the request for proposals (RFP) for implementing solar installations, an on-call consultant reviewed MassDOT properties and preliminarily identified parcels that would be good locations for solar installations. During the procurement process, the Office of General Council and the Procurement Office reviewed the drafted RFP and a sample of an agreement to ensure it complied with agency requirements. Solar developers then bid on the list of potential solar sites that MassDOT identified.

Based on the developers' qualifications and technical and financial proposals, MassDOT chose a developer who was among the most technically qualified and offered the best-value bid. Since the developer would sell the electricity to MassDOT through the PPA, MassDOT selected the developer with a sound technical solution at the lowest power price offer. Once the developer was selected, MassDOT engaged in the contract negotiation process, which involved lawyers specialized in standard DOT business and in solar development and financing because it was a new type of project and contract for the agency.

MassDOT and the developer entered into a master license agreement with a 20-year term for a maximum of 10 MW aggregated solar power generation capacity that would be delivered from multiple sites. For specific sites, MassDOT used addendums to the master agreement to specify the site conditions, installation, anticipated outputs, and PPA rates over time.

MassDOT and the developer have a review period at Year 15 to plan a course of action at the end of the agreement term. The default scenario at the end of the agreement is that the developer removes the installation and restores the site to its former condition. Other options that may be feasible are that MassDOT takes ownership of the installation at the end of the license agreement or that the developer and MassDOT extend the agreement.

The issue of power interconnection at each site was not addressed by the master agreement because utility companies required design specifics before they could determine whether they could accept the site's power to the grid, required upgrades, and costs. As a result, the developer had to perform its own site analysis and preliminary design for the sites on MassDOT's list and submit interconnection requests to the utility company. The utility company then conducted an engineering analysis to determine whether and what type of system protections and upgrades would be needed. The utility company also provided upgrade cost estimates as an added part of the engineering analysis. Following this step, some of the sites that MassDOT originally proposed were not economically feasible because of costly required system upgrades related to the interconnection due to the capacity, age, and distance of the existing infrastructure.

Public Involvement

For potential solar sites that were within a town's jurisdiction, MassDOT approached the town's leadership about the solar project. MassDOT usually attended the town's planning board meeting to talk about the solar project and implementation process. Some sites triggered environmental reviews at the town level due to their proximity to sensitive resources. MassDOT followed all outreach and formal approval processes for installing solar facilities that a town might require. This process also gave nearby residents an opportunity to voice concerns about the project.

Some of the public's concerns were related to visual impacts and glare. In one project, residents required a view analysis. Fortunately, a tree line blocked the view of the panels, which was sufficient to satisfy the residents' concern. Other residents had concerns about glare from the panels. MassDOT was able to address these concerns by providing scientific evidence that solar panels need to absorb light to generate electricity rather than reflect it.

Electricity Generation and Storage

During the contract negotiation period, the developer utilized industry-standard models to estimate electricity production at each site. The contract with MassDOT requires that a developer produce a minimum of 80 percent of the estimated electricity to avoid a penalty, which thus far has not been triggered. Under the PPA approach, the developer owns the solar installations and relies on the steady revenue from power sales to finance the projects in the long run.

No electricity storage is associated with the solar installations. MassDOT considered storage during the early program planning stage but decided not to pursue for cost reasons. In addition, there is no spot or ancillary services market that MassDOT can use and leverage.

Operation and Maintenance

During construction, the developer was required to restore the landscaping around the installation to its former condition. Throughout the 20-year contract period, the developer is also responsible for maintaining the site, including mowing.

The developer remotely monitors the solar installations' performance. It is in the developer's best interest to ensure the sites are productive since, as the owner of the installations, the developer only gets paid if the installations produce electricity. The solar installations are fully fenced, with high-voltage warning signs. MassDOT has not heard of any issues with vandalism or theft.

Plans and Opportunities

MassDOT is considering installing solar canopies at park-and-ride facilities and installing solar panels on existing noise barriers. These plans are in the early stages of development. Currently, MassDOT is not actively pursuing installing further solar installations in the right-of-way, primarily because current solar projects have been implemented at the most suitable locations.

Ohio DOT

Background

The Ohio solar site included panels that were installed on support frames by a company called First Solar and a second set of panels consisting of mats that were simply placed on the ground of the embankment by a company called Xunlight. The site and panels are owned by Ohio DOT (ODOT).

The solar site was installed as part of a larger bridge construction project, but the funding for the solar equipment came from a research grant under a separate project. Construction of the solar site was managed as part of the overall bridge construction project.

General Lessons Learned

ODOT staff provided the following lessons learned:

- The site requires little maintenance besides mowing, but that maintenance is difficult because the site is unique, and ODOT does not have spare parts readily available.
- Sometimes panels break due to items thrown from the overpass, but no one has ever broken into the site. Having a company with solar site experience to support and maintain the site if something fails is critical.
- The company that installed the solar mats went out of business, so ODOT had to eliminate the array because it could not be repaired. Ideally, solar panels that are used for a site should be able to be maintained or repaired by several companies and should not be specific to just one vendor.
- The site included a small building that was intended to provide storage for maintenance and spare material. It turned out that the building was not needed, and storage requirements could have been handled using one or more cabinets.

Project Development and Contracting

The goal of the project was to evaluate two different types of solar energy technologies—solar mats and solar panels—and to determine whether each system would produce sufficient energy for the lighting of the bridge and adjacent interchange. Recouping the cost of the installation or generating a profit was not a requirement for the project. Rather, it was considered a research project to determine the feasibility and economic viability of using the solar mats on other embankments throughout the state.

The project team consisted of staff from ODOT, the University of Toledo, and a solar energy consultant from a company called Advanced Distribution Generation. The solar energy consultant was in charge of making sure that the site operated properly and smoothly during the first year. The project was then handed over to ODOT for maintenance.

ODOT considered several sites, and the site ultimately selected had several benefits, including having a highway lighting controller in close vicinity to the site and not requiring heavy earth work. The site required two inverters to compare the two solar systems independently, which increased project costs. ODOT conducted a few public information meetings and issued a few press releases to announce the solar project. However, since the solar project was part of the overall bridge megaproject, few events focused only on the solar project, and most of the attention was given to the bridge.

Electricity Generation and Storage

The site is not producing as much energy as was initially estimated. After the first year, the difference between estimated and produced power was about 4 percent less than estimated. In

2019, the power produced was about 25 percent less than initially expected. The solar mats are only producing about 50 percent of what was initially estimated, in part due to a partial equipment failure.

Some estimates have put the payback period for the site at about 37 years, but because of panel degradation, that period is now likely to be longer. In addition, the panels are only rated to produce power for about 25 years. The increased payback period is a result of the lower-than-expected energy production and issues with the sale of the solar energy renewable energy credits. Selling the credits has not been as successful as hoped. At some point, ODOT hired a contractor to help sell the credits, but that effort has been mostly unsuccessful.

Storage was evaluated but not included in the system design since the power that is generated at the site was intended to be used on-site.

Operation and Maintenance

A company that helped build the system is periodically hired to perform basic maintenance and repairs. The site is fenced in, and ODOT never had any issues with people breaking into the site. The location of the solar mats on an embankment close to the roadway has been problematic. Occasionally, items and trash are thrown onto the mats, and some of them were broken and had to be replaced. For example, a few years ago someone threw a brick on one of the solar mats, which punctured the mat and turned off a portion of the system. The company that built the solar mats provided a quote to repair the mats but went out of business before the repair was completed. As a result, about 15 percent of the solar mats have been completely turned off.

Since a portion of the solar mats were shut down, ODOT has experienced some issues with the power inverter. Although the solar panels are offset from the roadway, a few of the solar panels were also damaged by thrown items and needed repair or replacement. Other than these issues and regular mowing, the solar panels have been mostly maintenance-free. ODOT has also experimented with rubber mats below the solar panels to keep weeds away from the panels and reduce the need for mowing.

Plans and Opportunities

The plan is to repair one of the inverters that has been turned off for some time. If the inverter cannot be repaired, the solar mat portion of the site may have to be turned off eventually. Currently, no plans exist for ODOT to construct additional solar sites in the state.

Oregon DOT

Background

In 2008, Oregon DOT implemented the first solar project in the United States on state right-of-way at Interstates 5 and 205 south of Portland (*8*). The site consists of 594 ground-mounted solar panels that generate about 104 kW, which offsets about a third of the energy needed for illuminating the interchange through net metering. The project involved a public-private partnership between Oregon DOT's Office of Innovation and Portland General Electric (PGE), as well as U.S. Bank as PGE's tax equity partner.

In 2012, Oregon DOT and PGE completed construction on the French Prairie Safety Rest Area solar site (formerly called Baldock Solar Station), located south of Wilsonville on Interstate 5 in Clackamas County. The site consists of 6,994 ground-mounted solar panels that generate about 1.75 MW on about 7 acres of Oregon DOT property. Annually, the site produces about 1.97 million kWh of renewable energy. Both the Interstate 5/205 and French Prairie Safety Rest Area solar sites qualified for the "public interest" exception under 23 USC 1.23(c), and both sites are operated and maintained by PGE, who leases the land from Oregon DOT (*9*).

General Lessons Learned

Since the original two projects, Oregon DOT has not developed additional solar sites. One reason is that the overall priorities of Oregon DOT have changed. Internally, the program was not formally continued at full capacity when the original program staff retired, so a lot of expertise was lost.

A recommendation for other DOTs is to formalize the solar program within the organizational structure of the DOT. Once the solar program becomes an official program within the DOT, it becomes easier to include solar activities in the long-range strategic plan or sustainability plan. Best practices highlighted by Oregon DOT include the following:

- Agencies should perform a comprehensive and systematic analysis of all DOT surplus properties. Tools such as GIS can be very useful if property information is available in a spatial database.

- Agencies should consider establishing the position of a program manager and program assistant. Solar project development and implementation take a lot of effort and cannot be accomplished on a part-time basis.

- Key to the success of a solar project is that DOT administration and state-level policies are aligned and are working toward the same goals. For example, a self-sufficient energy policy can create an incentive for solar energy projects.

- PPAs are useful contractual tools. More importantly, the utility needs to be involved in the development of the PPA and hopefully take the lead for most of the project details. It is a good practice not to invest too much time in a solar project until the DOT is convinced that there is buy-in from the utility.

- A solar project needs contracting and procurement flexibility. Oregon DOT was focused on the best value for Oregon, not necessarily the lowest project cost, which is why Oregon DOT included language to use local contractors, companies that created jobs in Oregon, and solar panels produced in Oregon.

- Once a site has been selected, outreach to members of the community and nearby neighborhoods should be performed to address any concerns they might have.
- The project team needs to be diverse and include staff with a legal background to draft legal documents and agreements.
- The environmental analysis for potential sites can be expensive, so it is important to prescreen sites that have a high probability of low environmental impact.

Project Development and Contracting

The Interstate 5 and 205 project was feasible because it used several incentives available at the time, including the following:

- State and federal renewable energy tax credits, including the federal investment tax credit.
- Accelerated depreciation accounting.
- A grant from the Energy Trust of Oregon.
- A grant from PGE's Clean Wind Fund.

As a regulated utility, PGE could not fully take advantage of the tax incentives, so it created a limited liability company (LLC) with U.S. Bank. The financial institution owned the project until tax incentives were derived, after which PGE acquired the project. Oregon DOT selected the site and owns the property, but PGE owns and operates the solar facility using a PPA with Oregon DOT.

The French Prairie Safety Rest Area solar site was also a public-private partnership between Oregon DOT and PGE. The relationship consisted of a sale-leaseback agreement rather than the LLC that was used for the project at Interstates 5 and 205. The agreement specified that PGE's financial institution owns the project until the tax benefits are derived, at which point PGE will acquire the project at fair market value. The sale-leaseback agreement also resulted in lower transaction costs with PGE's financial institution.

The power produced at the site generates SRECs, which the solar system owner earns for the electricity generated at the site. State agencies and utility companies can buy the certificates as proof of renewable energy generation to meet their goals under the state's renewable portfolio standard solar carve-out, which sets a specific goal for electricity generation from solar panels. The SRECs are used (retired) by PGE on behalf of its customers and Oregon DOT. Oregon DOT also receives a share of the SRECs generated by the site, and PGE submits an annual energy production report to Oregon DOT with specific SREC data. In addition, Oregon DOT receives a nominal site license monetary fee and credits for carbon offsets.

Using SRECs instead of net metering provides several benefits to Oregon DOT. Under Federal Trade Commission rules, environmental attributes of solar energy are assigned to the owner of the SRECs. Owning a share of them gives Oregon DOT a clear and defensible claim to its share of renewable energy. Further, PGE's net metering policy limits benefits to the amount of electricity that can be offset at the site—if the site produces more electricity than needed locally, Oregon DOT will not generate any revenue. SRECs can be sold, but so far Oregon DOT has chosen not to sell any certificates.

Although public carbon policy assigns the carbon offsets to the utility providing power at the site, SRECs are intended to include carbon offsets. Since PGE assigns a share of the SRECs to Oregon DOT, it gives Oregon DOT a claim for some of the carbon offsets generated at the site.

Contractors must meet strict environmental compliance regulations and perform product lifecycle stewardship, which includes removal of the site once the facility has reached the end of its useful life.

Electricity Generation and Storage

The I-5/I-205 Solar Demonstration Site is net metered and produces enough energy to offset more than a third of the energy needed for freeway illumination at the site. The actual monthly generation may fluctuate but can be confirmed with PGE.

The French Prairie Rest Area solar site is also operated and maintained by PGE. At this larger site, Oregon DOT receives a percentage of energy credits (SRECs) generated through 1.97 million kWh of annual production. The energy and credits generated at this site are retired by PGE on behalf of Oregon DOT and tracked by the Western Renewable Energy Generation Information System (WREGIS), an independent renewable energy tracking system for the region. WREGIS tracks renewable energy generation from units that register in the system by using verifiable data. The energy generation capacity for the two solar highway sites is available to the public and listed in the description of the projects on Oregon DOT's solar website.

Plans and Opportunities

Oregon DOT's solar sites do not have battery storage. PGE is planning to create a battery site next to a solar site to provide additional capacity and resilience to the energy grid.

Vermont Agency of Transportation

Background

The main goal of the Vermont solar program was to make state right-of-way available at a low cost to encourage solar development, with a secondary goal of saving Vermont Agency of Transportation (VTrans) funds. The Fair Haven Welcome Center solar project is a 75-kW solar installation in the VTrans right-of-way. The project was built as part of VTrans' commitment to generating 25 percent of its electricity use from renewable resources by 2030.

General Lessons Learned

Staff from VTrans offered the following lessons learned regarding solar projects:

- For the Fair Haven Welcome Center project, VTrans assigned a solar project manager who had many other outside responsibilities. If VTrans seriously pursues solar projects in the future, one recommendation is to have a solar project manager in charge of project development who has sufficient available time.
- Vermont has experienced significant local opposition to solar projects; as a result, large-scale solar projects have become difficult to implement.
- VTrans currently does not have staff dedicated to the development of solar projects, which significantly limits the ability to gather right-of-way data to support solar projects.
- Vermont's electric utilities currently have no issues with meeting the state's renewable energy standard. As a result, there is currently no pressure from the state utilities to make VTrans right-of-way available for solar projects.
- The statewide cap on net metering is 500 kW of installed electricity generation, which the state government has reached, and which therefore has limited VTrans' solar project development activities.

Project Development and Contracting

The Fair Haven Rest Area project was built on surplus VTrans right-of-way and uses net metering. The project was intended to showcase Vermont's commitment to a renewable energy future. VTrans staff included the solar project manager and staff from the right-of-way department, the mapping division, and contract administration.

VTrans amended its utility accommodation rules to accommodate solar utility sites in the state right-of-way. VTrans then used an agency-wide process to identify and screen potential sites for solar installations. Sites where VTrans installed solar net metering include district garages, an airport, and the Fair Haven Rest Area.

A VTrans staff member took on the role of solar project manager in addition to other responsibilities. Although the solar projects were successful, VTrans underestimated the complexity and the amount of effort needed. VTrans found that it takes a lot of perseverance and time to complete renewable energy projects. VTrans is not pursuing additional solar projects at this time. This is due primarily to the lack of net metering, combined with Vermont's clean grid and high degree of solar net metering that already exists and that continues to be developed.

Operation and Maintenance

In general, maintenance and landscape design are very important issues in Vermont. For example, chain-link fences that are used in other states are effective, but the aesthetics may not work in Vermont.

Plans and Opportunities

Net Metering

Around 2017, the State of Vermont instituted a cap on net metering. This change resulted in an almost immediate halt of all VTrans solar projects in the right-of-way. As a result, VTrans evaluated other options to determine if solar projects could be feasible without net metering. VTrans accepted the new law because VTrans found that state regulators used the net metering cap to essentially try to balance the promotion of renewable energy with an additional burden for rate payers. In places where the net metering cap is being reached, VTrans may evaluate options where adjacent businesses that have not reached the net metering cap might be able to offtake that electricity.

Based on discussions with FHWA and the Vermont Department of Public Service, VTrans drafted an RFP that was intended to be used for project bids from solar developers. However, the draft does not include detailed information about potential sites available for development. Until information about potential sites become available, the request cannot be sent to developers, so the process to issue the request has been stalled.

Power Purchase Agreements

VTrans may still be open to projects that would involve PPAs. Vermont's renewable energy standard, which applies to state electric utilities, is becoming increasingly strict. However, it appears that the state's utilities can meet the stricter standards without the use of transportation right-of-way. As a result, VTrans has not been approached to make more state property available to utilities to build new solar facilities. Opportunities for PPAs seem to exist for the state, but pursuing these potential opportunities is not a priority at this time.

Small-Scale Solar Projects

Large-scale solar projects in general have experienced significant local opposition. It appears that many people simply do not like the appearance of solar sites. For similar reasons, the state is no longer involved in ridgeline wind development due to local opposition. As a result, Vermont is now focusing more on small-scale solar installations for individual homes and businesses that still allow net metering.

Fair Market Value Requirement

The FHWA Division in Vermont decided that the public interest exception does not apply to solar projects. One of the deciding factors was that a developer would make a profit, so VTrans still needs to charge fair market value. However, there are different ways to calculate fair market values, resulting in a range of rent values. For example, instead of using appraisals or adjacent parcel values, fair market value can be determined by using the bids received in the bidding process, which can end up significantly lower than the appraised value.

Renewable Energy Areas of Interest

VTrans is very active in a statewide plug-in electric vehicle incentive program. VTrans is also working on legislation to set up a dealer and salesforce incentive program. VTrans is on an interagency team that is using funding from the Volkswagen settlement to build electric vehicle charging infrastructure. The funding will run out soon, so VTrans is working on adding general funds to continue that effort. VTrans is also working on highway user fees for electric vehicles, rate design for electric vehicle charging, and charging weights and measures. Solar in the right-of-way is currently not on the list of priorities.

However, VTrans is very interested in solar canopies in parking areas and park-and-rides. Canopies help keep snow, rain, and sun off parked cars and can produce power. Concerns are that the sites might get too expensive because of the required support structures, and issues with snowplowing might exist. If the technology is economical, VTrans might pursue that option.

Regarding electricity storage, a company in Vermont called iSun focuses on solar-powered electric vehicle charging stations with on-site storage. VTrans has had a series of meetings to determine if there is an opportunity for a public-private partnership between VTrans and iSun.

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APPENDIX: LIST OF INTERVIEW QUESTIONS

General Lessons Learned

1. What issues do you wish you knew about earlier?
    - For example, risks, political issues, cost of maintenance/ownership, contractual misinterpretations/misunderstandings, permitting/code requirements, etc.

Project Development

Overcoming Institutional Inertia

2. What were the chief internal arguments against solar deployments?
3. How were arguments against solar deployments mitigated?
4. Which divisions/programs were the biggest advocates for the solar project, and which were the biggest opponents?
5. What was done to bring management on board or develop their support?

Best Practices

6. Knowing what you know now, if you were putting together a team of people for a solar project, what would that team look like? Would you involve:
    - Lawyers, engineers, planners, maintenance staff, finance/budget analysts, ROW analysts, construction staff, other?
7. Did your project have a solar project manager?
    - Why/why not?
        - If so, what were the project manager's responsibilities?
    - Any lessons learned from this?
8. Did your solar project team/project manager have experience in the energy industry or experience in renewable energy design?
    - If so, what type of experience?
9. What are good practices in putting together a team to develop a solar project?
10. What type of expertise is critical on a team charged with the development of a solar project?

Project Implementation

11. What form did project initiation take?
    - For example, was installation part of/included in design of another project, or was it a separate pilot? If included in design of another project, at which point in the project development process?
12. Did your agency work with other state agencies to develop the solar project?
    - If so, which states, and what kind of information did they provide?
13. What stakeholders were actively engaged, and what was done to get them engaged?
14. How was the public involved and engaged in the project?
15. How was the project focused/positioned?
    - Sustainability/green.
    - Social/environmental justice.
    - Financially.
    - Other.
16. How did you make use of media (websites, newsletters, other)?
17. What went well in terms of project implementation?
    - What did not go so well?

Electricity Generation

18. What are the primary loads (general grid, or state-owned property)?
    - How were the primary loads projected prior to installation?
19. Are you generating as much electricity as you expected?
    - If not, what issues are preventing you from generating the expected amounts?
20. Did you oversize your system to overcome panel grime and dirt build-up?
21. Did you have any premature component failures?
22. How do you monitor site performance?

Electricity Use and Storage

23. In light of public safety power shutdowns during adverse weather conditions in California, how are your systems designed to perform during grid-wide power outages?
24. Do you use any electricity storage systems?
25. Are there any efforts underway to address local energy storage?

26. In light of too much solar production and not enough users (California Duck Curve), what are impediments to implementing solar projects?
    - What are the impediments to creating/obtaining partnerships?
    - What is the current state of creating/obtaining partnerships in your jurisdiction?
27. Do you use any smaller systems to accommodate local needs, i.e., signalized intersection/lighting needs?

Maintenance

28. Do you have issues with vandalism and/or theft?
    - If so, how are they addressed?
29. What kind of landscaping design do you use around the solar facility?
    - What are impacts to mowing/weed abatement activities due to the facility?
    - Are there issues with unsheltered people using the facility for shelter?

Plans and Opportunities

30. Did the project estimate or establish a date when the site is expected to be no longer useful (e.g., the cost of maintenance is higher than the value of energy being produced)?
    - How was that date established?
31. Are you planning to expand the site in the future?
    - What conditions would need to be present to expand the solar installation?
32. Do you have plans for additional solar sites?
    - If so, what type of solar sites?

APPENDIX C: SUMMARY OF RULES AND REGULATIONS

Caltrans Project No. P1253
Caltrans Task No. 3177

Solar Power Initiative Using Caltrans Right-of-Way—Summary of Rules and Regulations

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CALIFORNIA DEPARTMENT OF TRANSPORTATION

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INTRODUCTION

Numerous regulatory rules, regulations, and policies affect the California Department of Transportation's (Caltrans') ability to install utility-grade solar generation sites within the right-of-way. Regulatory agencies vary, from federal-level entities to California utility companies. This summary identifies the rules, regulations, and policies that affect Caltrans' ability to install utility-grade solar generation sites in the Caltrans right-of-way. The summary includes a detailed review of federal and state regulations as well as local utility companies' rules and policies concerning power purchase agreements and partnerships for the installation of utility-grade solar generation sites. In addition, the summary highlights current incentives available to Caltrans for the installation of utility-grade solar facilities in the right-of-way.

BACKGROUND

In 1988, the Federal Highway Administration (FHWA) revised Section 645.209 of the Code of Federal Regulations (CFR) to instruct state departments of transportation (DOTs) to follow the American Association of State Highway and Transportation Officials' (AASHTO's) *Policy on the Accommodation of Utilities Within Freeway Right-of-Way* as before, or to adopt their own policies (*1, 2*). This gave states the ability to implement their own policies, and today all states have utility accommodation rules (UARs) approved by FHWA.

In addition to the guiding principles provided by AASHTO, FHWA provides a list of provisions in 23 CFR 645.211 that should be included in each state's UARs (*3*). Updated in 2005, the AASHTO policy states that DOTs have "various degrees of authority to regulate the use of utilities within highway rights-of-way generally through their authority to designate and to control the use made of right-of-way acquired for public highway purposes" (*2*). The agency's authority depends not only on the federal law but also the individual laws and regulations of the state. To accommodate utilities in the state right-of-way, states must follow the procedures outlined in their UARs to evaluate and approve individual applications for utility facilities in their right-of-way.

Most states provide free access to public utilities on state right-of-way or right-of-way that is not access-controlled. Many states do not allow longitudinal utility installations on controlled-access right-of-way or require compensation that might be defined in a lease agreement or shared resources agreement.

FEDERAL GUIDANCE

FHWA provides two procedures for states seeking guidance regarding the installation of renewable energy generation projects in highway right-of-way purchased with federal funds. The option depends on whether the state defines a renewable energy generation facility as a utility and whether the project serves the public. The first procedure relates to states that do consider a renewable energy generation facility to be a utility, and the second procedure applies to states that do not include renewable energy under their definition of a utility. The federal definition for a utility can be found in Title 23 of the CFR Section 645.207 and includes a "privately, publicly or cooperatively owned line, facility, or system" used to produce, transmit, or distribute power and electricity (*4*). FHWA states that renewable energy projects "that are connected to the public utility grid or provide electricity used by a public agency such as the State DOT would generally be considered as serving the public" (*5*).

A review of state regulations and rules found that states typically define a public utility as any entity or corporation providing water, electricity, gas, telecommunications, or transportation to the public. Ownership does not necessarily have to be public, but the service must be for public use. There are some instances where a publicly owned utility can be regulated differently. A utility can be considered a private utility if it provides a service to a small number of customers or to private land as opposed to the general public.

Renewable Energy Facility Is a Utility

If a state's UARs define a renewable energy generation facility as a utility and the project will serve the public, then Chapter 1 of Title 23 of the CFR Part 645 of Subchapter G regarding the accommodation of utilities applies (*6*). When the facility is considered a utility, FHWA does not require a DOT to charge a fee for the utility use,[1] leaving any fee requirement up to the state (*7*). The Caltrans *Encroachment Permits Manual* provides a detailed description of methods and procedures in the issuance of encroachment permits (*8*).

Renewable Energy Facility Is Not a Utility

If the state's UARs do not define a renewable energy generation facility as a utility, if the project does not serve the public, or if the owner of the renewable energy facility elects not to apply for a utility permit, the state DOT may execute a right-of-way use agreement under 23 CFR 710 and subject to 23 CFR 771 (Environmental Impact and Related Procedures) (*9*, *10*). It is up to FHWA to determine on a project-by-project basis whether the use is in the public interest; is consistent with the continued use, operations, maintenance, and safety of the facility; and does not impair the highway or interfere with the safety of the traffic (*5*). Except for interstate highways, this responsibility may be assigned to the state DOT through the Stewardship and Oversight Agreement. The Stewardship and Oversight Agreement that Caltrans executed with FHWA in 2015 maintains that interstate right-of-way use agreements are approved by FHWA, and that other non-highway use and occupancy under 23 CFR 1.23(c) is approved by FHWA for interstates and by Caltrans for non-interstate highways (*11*, *12*).

[1] This exception to 23 USC 156(c) is based on conference report language for Section 126 of the Federal-Aid Highway Act of 1987 (Title I of the Surface Transportation and Uniform Relocation Assistance Act of 1987, Pub. L. 100-17 [Apr. 2, 1987]). With respect to 23 USC 156 provisions on income from right-of-way, added by the act, the report states, "The charges and disposition of fees for utility use and occupancy of right-of-way will continue to be governed by 23 CFR 645" (H.R. Conf. Rep. 100-27). FHWA also has broad authority to establish utility accommodation criteria under 23 USC 109(l).

Fair Market Value Compensation

If the right-of-way was acquired using Title 23 United States Code (USC) funding, fair market compensation is required for use of the right-of-way and use or disposal of all property interests, using the state's definition for fair market value defined by state statute or state court decisions (*9*). For example, Caltrans rules for fair market value are defined by the California Code of Civil Procedure Section 1263.320, and policies for right-of-way use and disposal are provided by the Caltrans *Project Development Process Manual* (*13*, *14*). In addition, the Caltrans *Right of Way Manual* provides a discussion on fair market value considerations for various right-of-way acquisition and disposal scenarios (*15*).

Exceptions to fair market compensation might be granted by FHWA on a case-by-case basis, including projects in the overall public interest, for nonproprietary governmental use, and involving use of right-of-way by public utilities in accordance with 23 CFR Part 645 (*6*).

Changes to Access Control

FHWA requires the state DOT to obtain written approval prior to any temporary or permanent modification of access control on the interstate system as well as non-interstate federal-aid highways.[2] The Stewardship and Oversight Agreement between FHWA and the state DOT details the approving authority for highways on the National Highway System (NHS), and the DOT should approve access control modifications to all non-NHS highways (*9*). In California, the Stewardship and Oversight Agreement with FHWA further defines that Interstate System access changes during the preliminary design phase of a project must be approved by FHWA, and that the disposal of access control both at fair market value and less than fair market value, both during the design phase of a project or the operation phase of the highway, must be approved by FHWA (*12*).

Environmental Review

Projects involving federal funds or approval (including those delegated by FHWA to the DOT) are required to comply with the National Environmental Policy Act (NEPA) (*10*). In California, projects are further required to adhere to the California Environmental Quality Act (CEQA) (*16*). The process and documentation will vary depending on the site selected for the renewable energy facility. FHWA has found that the "State DOT experience so far shows that selecting sites on vacant lawns along highways, away from sensitive resources, makes it more likely that the project will be classified as a Categorical Exclusion (CE) and require only limited NEPA documentation" (*5*). The Caltrans Environmental Division provides more information about compliance with NEPA and CEQA (*17*).

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[2] The approval applies to segments that have received federal-aid funds.

Bureau of Land Management Solar Energy Program (Western Solar Plan)

The Bureau of Land Management (BLM) created the Solar Energy Program in 2012 through the *Final Programmatic Environmental Impact Statement for Solar Energy Development in Six Southwestern States and the Approved Resource Management Plan Amendments/Record of Decision (ROD) for Solar Development in Six Southwestern States* for utility-scale renewable energy development on BLM-administered land (*18*). BLM lists several laws, orders, and regulations that have helped facilitate the development of renewable energy facilities on public lands:

- Executive Order 13212 of 2001, Actions to Expedite Energy-Related Projects, which orders agencies to expedite the review of permits to help accelerate project completion (*19*).
- Energy Policy Act of 2005, which addresses energy production and focuses on issues such as energy efficiency and energy tax incentives (*20*).
- Energy Independence and Security Act of 2007, which works to increase U.S. energy independence and security by creating energy reduction goals and requirements (*21*).
- U.S. Department of the Interior Secretarial Order 2385 of 2010, Renewable Energy Development by the Department of the Interior, which prioritizes the development of renewable energy, sets forth the department's roles and responsibilities, and establishes a task force (*22*).
- Executive Order 13514 of 2009, Federal Leadership in Environmental, Energy, and Economic Performance, which orders agencies to increase energy-efficient measures and sets forth target goals to be met through each agency's Strategic Sustainability Performance Plan (*23*).
- Executive Order 13783 of 2017, Promoting Energy Independence and Economic Growth, which orders all agencies to review all existing regulations and other guiding documents that could potentially obstruct the development or use of energy resources (*24*).
- U.S. Department of the Interior Secretarial Order 3349, American Energy Independence, which calls for the reexamination of the department's policies and practices in order to better balance the need for job creation with the conservation strategies (*25*).

The program encompasses Arizona, California, Colorado, Nevada, New Mexico, and Utah. BLM defines utility-scale projects as those with 20 MW or greater capacity that is provided to the electricity grid. The program specifies lands that are excluded from utility-scale solar development and identifies solar energy zones (SEZs) that are appropriate, prioritized locations. In 2016, BLM published right-of-way regulations in 43 CFR 2800 that detail the applicable authorization policies. The program also allows for development outside of SEZs through a variance process (*26*).

The ROD allows BLM to make individual decisions regarding each solar energy project application. In accordance with NEPA, BLM will complete a site-specific review of each project application and a NEPA analysis of lands within an SEZ.

STATE GUIDANCE

This section provides an overview of rules, regulations, and policies of California and other states with regard to the installation of utility-scale solar facilities in the right-of-way. The section discusses definitions of public utilities, right-of-way access, renewable portfolio standards and goals, and net metering and power purchase agreements; presents considerations for land conservation; and provides an overview of funding mechanisms. A more detailed discussion of financing strategies for utility-scale solar facilities is provided in a separate document as part of the Task 6 deliverable.

Caltrans adopted AASHTO's 2005 Utility Accommodation Policy and has additional rules for utility accommodation and encroachments that are covered under the California Streets and Highways Code (*2*). For example, Section 700 and following deal with special provisions for utilities on freeways (*27*).

In addition to the summary provided here, the Caltrans *Project Development Procedures Manual* provides information about policies and procedures for Caltrans projects, including a discussion of responsibilities for utility owners in Chapter 8 and a description of utility encroachment policies in Chapter 17 (*14*).

Public Utility Definitions and Solar Facilities

California

California's statutory definition of a public utility is provided in California Public Utilities Code Section 216 (*28*). According to the code, a public utility "includes every common carrier, toll bridge corporation, pipeline corporation, gas corporation, electrical corporation, telephone corporation, telegraph corporation, water corporation, sewer system corporation, and heat corporation, where the service is performed for, or the commodity is delivered to, the public or any portion thereof" (*28*). Subsections of this statute specify provisions that limit what can be considered a public utility and impact whether renewable-energy-generating facilities are a utility or not under California law. For example, regarding the generation of electricity, the statute states in subsection (h) that a corporation is not considered a utility solely because it generates electricity that is sold to the public:

> The ownership, control, operation, or management of an electric plant used for direct transactions or participation directly or indirectly in direct transactions, as permitted by subdivision (b) of Section 365, sales into a market established and operated by the Independent System Operator or any other wholesale electricity market, or the use or sale as permitted under subdivisions (b) to (d), inclusive, of Section 218, shall not make a

> corporation or person a public utility within the meaning of this section solely because of that ownership, participation, or sale. (*29*)

Similarly, regarding the generation of heat from renewable sources, the statute specifies in subsection (e) that a corporation is not considered a utility solely because it sells heat generated from a solar resource to a utility or the public:

> Any corporation or person engaged directly or indirectly in developing, producing, transmitting, distributing, delivering, or selling any form of heat derived from geothermal or solar resources or from cogeneration technology to any privately owned or publicly owned public utility, or to the public or any portion thereof, is not a public utility within the meaning of this section solely by reason of engaging in any of those activities. (*30*)

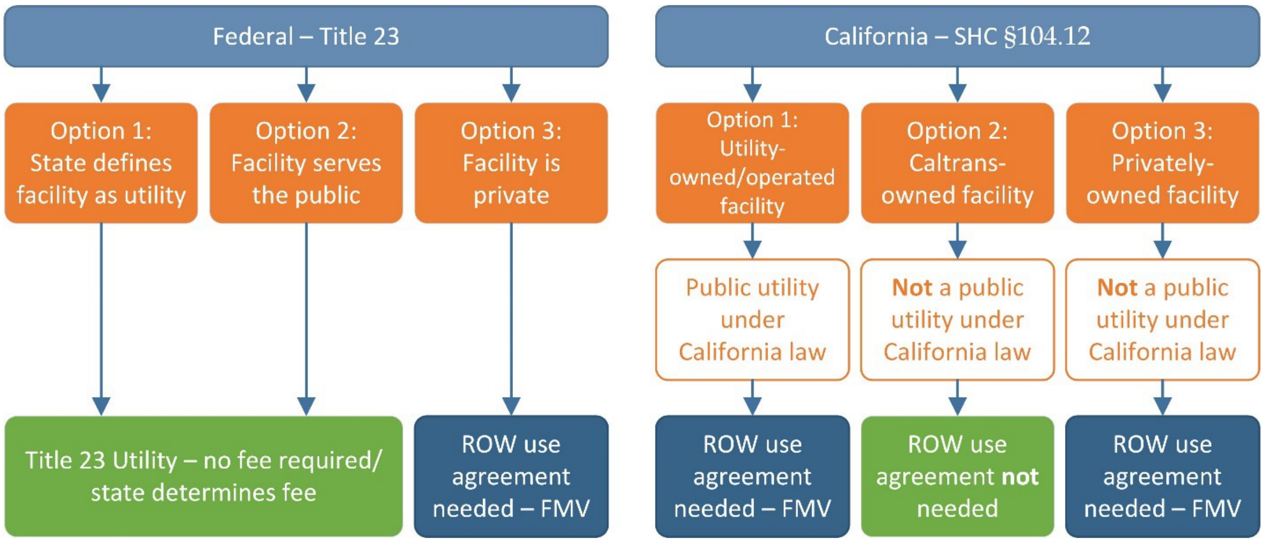
Subsection (d) of the statute clarifies that a corporation that produces power from other than a conventional power source is not solely considered a utility because it sells that power to the public:

> Ownership or operation of a facility that employs cogeneration technology or produces power from other than a conventional power source or the ownership or operation of a facility which employs landfill gas technology does not make a corporation or person a public utility within the meaning of this section solely because of the ownership or operation of that facility. (*31*)

California's definition of the "public" does not include direct end users that are provided electricity through an independent system operator. The independent system is not available to the public at large, but instead to a small market of consumers that have entered into an agreement with the corporation that is generating electricity (*28, 32*). This would restrict developers of solar facilities from being considered a utility unless the facility did intend to provide electricity to the public at large. If a solar facility is considered a utility, the owner and operator of that facility would have to comply with the California Public Utilities Commission (CPUC) rules and regulations.

Overall, the law specifies that a company that owns and operates solar facilities but does not sell the generated electricity or heat directly to the public is not considered a utility. However, if a utility company is the owner of the solar facility, the solar installation would simply be considered a part of the company's operation and therefore fall under the definition and regulation of a public utility.

California Streets and Highways Code Section 117 provides Caltrans the authority to issue permits for the location in the right-of-way of any structures or fixtures necessary to telegraph, telephone, or electric power lines or of any ditches, pipes, drains, sewers, or underground structures (*33*). As a result, the permitting of utilities in the right-of-way targets facilities that transmit but not necessarily produce a good or service. Electrical production in the state right-of-way would not be considered transmission and therefore would require a Right-of-Way Use Agreement under 23 CFR 710.405 and Streets and Highways Code 104.12. To clarify, Caltrans updated Chapter 17 of its Project Development Procedures Manual, which states that "proposals for installation of infrastructure to generate sustainable energy sources, such as solar (…) are reviewed and processed as right-of-way use agreements" (*14*). Figure 1 provides a comparison of options to define a solar energy facility under federal law and the requirements for solar energy facilities under California law.



Note: SHC (Streets and Highways Code), FMV (Fair Market Value), ROW (right-of-way).

Figure 1. Requirements for Solar Energy Facilities under Federal and California Law.

Other States

AASHTO's *Policy on the Accommodation of Utilities Within Freeway Right-of-Way* allows for the siting of utility facilities within the right-of-way (*2*). States will often provide greater provisions that govern the access and use by utilities of a right-of-way in their UARs. In Oregon, solar and wind resources are not included under the state's definition of a public utility, regardless of the number of customers served by that resource (*34*). In other states, the determination of whether solar installations and renewable energy facilities can be considered a utility, and therefore follow utility rules regarding accommodation in a right-of-way, is dependent on the state and often the size, location, and nature of the entity that owns the solar installation.

Some states specifically declare that ownership of renewable energy facilities does not make the corporation or owner a public utility unless the entity otherwise conforms to the definition of a public utility. For example, Colorado State law provides the following:

> Any corporation or person engaged directly or indirectly in developing, producing, transmitting, distributing, delivering, or selling any form of heat derived from geothermal or solar resources or from cogeneration technology to any privately owned or publicly owned public utility, or to the public or any portion thereof, is not a public utility within the meaning of this section solely by reason of engaging in any of those activities. (*35*)

Similarly, North Carolina removes the developer or operator of a renewable energy facility from the definition of a public utility, stating that:

> the term "public utility" shall not include persons who construct or operate an electric generating facility, the primary purpose of which facility is either for (i) a person's own use and not for the primary purpose of producing electricity, heat, or steam for sale to or for the public for compensation or (ii) a person who constructs or operates an eligible solar energy facility on the site of a customer's property and leases such facility to that customer. (*36*)

Kansas has a similar provision that excludes a company or corporation that sells electricity wholesale, rather than to residential consumers, from its definition of a public utility (*37*).

Right-of-Way Access

Most states convey the authority to regulate access and placement or construction on a right-of-way within the state highway system to the DOT or similar state highway administration. Typically, state legislation, codes, or statutes require that this access be regulated in a fair, reasonable, nondiscriminatory, and competitively neutral manner. These fair and reasonable provisions also apply to any fees for access, with most states requiring that the fees be related to the costs incurred by the DOT during the permitting or leasing process. Additionally, public utilities in most states must follow the rules of a state public utilities commission or public service commission. Most of those commissions regulate the utility-to-consumer relationship to ensure that all construction or placement is in the public interest rather than regulate access to right-of-way. The rules for access to the right-of-way can vary in cases of state highways within municipalities. The state DOT often has ultimate control but, when deemed necessary, can allow municipalities to regulate right-of-way within their boundaries.

Renewable Portfolio Standards and Goals

A renewable portfolio standard (RPS) can be defined as a "regulatory mandate that require[s] electric utilities and other retail electric providers to supply a minimum amount of energy from renewable sources" (*38*). As of 2019, 29 states plus the District of Columbia had established RPSs, and 8 states had established renewable energy goals (*39*).

California's RPS was established in 2002 by Senate Bill 1078 (*40*). Since its establishment, various legislative actions have made changes or adjustments in order to meet the renewable energy targets. Senate Bill 350 in 2015 increased the RPS procurement requirements of retail sellers and publicly owned utilities to 50 percent by 2030. The 100 Percent Clean Energy Act of 2018 (Senate Bill 100) amended sections in the Public Utilities Code to raise the percentage of energy obtained from renewable energy sources (*41*).

Successive governors have issued several executive orders and bills over the years that aimed to improve California's environmental footprint by reducing emissions, energy consumption, and greenhouse gases. The California Energy Commission currently handles guidance and implementation of the standards with assistance from the CPUC (*32*). The following is a summary of those executive orders and bills:

- Executive Order S-20 of 2004, mandating the reduction of electricity consumption in buildings (*42*).
- The California Global Warming Solutions Act of 2006, requiring the state board to implement greenhouse gas regulations to reduce emissions. These regulations include reporting, monitoring, enforcing, and efficiently managing emissions (*43*).
- Executive Order B-16 of 2012, requiring agencies to streamline zero-emission vehicle commercialization and use (*44*).
- Executive Order B-18 of 2012, mandating that state agencies reduce greenhouse gas emissions by 10 percent before 2015 and 20 percent by 2020. Additionally, state agencies must reduce purchases of grid-based energy (*45*). Executive Order B-18 led to the development of the Clean Renewable Energy Bond (CREB) Program, as described later in this report.
- Executive Order B-30 of 2015, requiring emission reductions below 1990 levels (*46*).
- Executive Order B-48 of 2018, requiring state agencies to work with the private sector to reach 5 million zero-emission vehicles on the road by 2030 and invest in fueling infrastructure (*47*).
- Executive Order B-55 of 2018, mandating that the state reach carbon neutrality before 2045 (*48*).
- Executive Order N-19 of 2019, creating the Climate Investment Framework and directing the state transportation agency to reduce emissions from the transportation sector (*49*).

Utilities can typically demonstrate their compliance with the law using renewable energy certificates. These certificates are described as tradeable environmental commodities representing megawatt hours of renewable electricity.

Distributed Power Generation

Many states support the distributed generation of power by small and individual power generation facilities to relieve electricity supply constraints. In California, distributed power generation has been a longstanding policy of CPUC, as stated by the California Legislature (*50*). Under direction of the legislature and its own initiative, CPUC has implemented several distributed power generation programs:

- The California Solar Initiative (*51*).
- The Self-Generation Incentive Program (*52*).

- Net Energy Metering (*53*).
- Virtual Net Energy Metering.[3]
- The Renewable Feed-In Tariff Program (*54*).
- The Efficient Combined Heat and Power Tariff Program (*54*).
- The Investor Owned Utilities' Solar Photovoltaic (IOU Solar PV) Program.[4]
- Qualifying Facilities (QFs) of Less Than 20 Megawatts (MW) Program (*55*).
- The Renewable Auction Mechanism (RAM) Program.[5]

In 2016, CPUC endorsed the Distributed Energy Action Plan to align the commission's vision and actions for distributed energy resources, and then updated the plan in 2017 (*56*, *57*). The plan provides a roadmap to coordinate activities of CPUC and directly supports several CPUC directives to guide staff activities throughout the agency.

Electric Rule 21

Rule 21 was first adopted by CPUC in 1982 to meet the needs of small, non-utility-owned generating facilities with the intent to connect these facilities to the electric grid. This physical linking of a private renewable energy facility to the regional utility grid, including necessary transformation, is referred to as "interconnection" (*58*). This linkage is typically managed by the local electric utility, and standards are set by the state.

Since its adoption, Rule 21 has been continuously modified and revised. Typically, CPUC will start the process by issuing an order instituting a rulemaking, including the general topics that will be considered by the rulemaking. With regard to interconnection, CPUC established in Resolution AJ-347 in 2017 the Interconnection Discussion Forum as an informal venue for stakeholders to discuss interconnection practices and policies (*59*).

[3] The Virtual Net Metering Program was created on CPUC's own motion in D.11-07-031, California Solar Initiative Phase One Modifications. Ongoing implementation of the Virtual Net Energy Metering Program occurs within R.10-05-044, Order Instituting Rulemaking Regarding Policies, Procedures and Rules for the California Solar Initiative, the Self-Generation Incentive Program and Other Distributed Generation Issues.

[4] The IOU Solar PV Program was created on CPUC's own motion, and the commission implemented the program in separate application proceedings for each utility. The decisions implementing the program (and the application number) for each utility include D.09-06-049 issued June 18, 2009, in A.08-03-015; D.10-04-052 issued April 22, 2010, in A.09-02-029; and D.10-09-016 issued September 2, 2010, in A.08-07-017.

[5] The Renewable Auction Mechanism was created on CPUC's own motion in D.10-12-048, Decision Adopting the Renewable Auction Mechanism, issued December 16, 2010, in R.08-08-009. Ongoing implementation of the Renewable Auction Mechanism occurs within R.11-05-005.

CPUC modified Rule 21 in 1999 with help of the California Energy Commission to quickly identify generating facilities that would be unlikely to cause disruptions of the electrical grid. Over the next few years, CPUC added the following decisions to address additional interconnection issues under Rulemaking 11-09-011:

- D.12-09-018 issued September 20, 2012, which adopted a settlement agreement focused on the interconnection study process, including a "fast track" and a "detailed study" process (*60*).
- D.14-12-035 issued December 18, 2014, which revised Rule 21 to require "smart" inverters for Pacific Gas and Electric Company (PG&E), Southern California Edison Company (SCE), and San Diego Gas & Electric Company (SDG&E) based on recommendations by the Smart Invert Working Group's January 2014 report (*61*).
- D.16-06-052 issued June 23, 2016, which made several changes to Rule 21 including changes to the Rule 21 Pre-Application Report and the creation of a unit cost guide (*62*).

Rule 21 does not apply to facilities that intend to connect with wholesale markets regulated under the Federal Energy Regulatory Commission (FERC), which typically apply for interconnection under the FERC Wholesale Distribution Access Tariff when connecting to the distribution system, or the CAISO Tariff when connecting to the transmission system (*59*). Rule 21 specifically relates to the following items:

- Procedures and timeframes for reviewing applications.
- Fee schedules to process applications and perform impact studies.
- Pro forma application and agreement forms.
- Allocation of interconnection costs.
- Provisions specific to net-energy-metered facilities.
- Technical operating parameters.
- Certification and testing criteria.
- Technical requirements for inverters.
- Metering and monitoring requirements.
- Procedures for dispute resolution.

On July 13, 2017, CPUC issued an order for a new rulemaking process under Rulemaking 17-07-007 (*63*). A topic currently being discussed is the incorporation of the utilities' integration capacity analysis tools, which might better inform interconnection siting decisions and further streamline the Rule 21 fast track process (*63*).

In accordance with Electric Rule 21, utility companies have produced manuals and handbooks regarding interconnection policies and procedures (*59*). These handbooks typically map out the interconnection technical procedures as well as any net metering policies. As part of the legal review, the research team reviewed the following guidance manuals:

- Sacramento Municipal Utility District (SMUD):
  - *Rate Policy and Procedures Manual* (*64*).
- San Diego Gas & Electric:
  - *Standard Large Generator Interconnection Procedures* (*65*).
  - *Generation Interconnection Handbook* (*66*).
- Pacific Power:
  - *Distributed Energy Resource (DER) Interconnection Policy* (*67*).
- Pacific Gas & Electric:
  - *Distribution Interconnection Handbook* (*68*).
- Southern California Edison Company:
  - *Generator Interconnection Procedures* (*69*).
  - *The Interconnection Handbook* (70).
  - *Net Metering Interconnection Handbook* (*71*).

The guidance typically begins by outlining the types of facilities that are covered in the handbook and then explains the request and application processes along with any required feasibility or impact studies. Technical topics include design and operation requirements; control, protection, and safety equipment requirements; and maintenance requirements. The guides also cover topics such as access, ownership, and responsible parties. Net metering interconnection policies are also explained, as well as any testing and certification criteria.

Net Energy Metering

California describes net energy metering as a "special billing arrangement that provides credit to customers with solar PV (photovoltaic) systems for the full retail value of the electricity their system generates" (*72*). Under a net metering agreement, the meter tracks the electricity consumption of the customer as well as the excess energy delivered back into the utility grid. Over the course of a year, the customer only pays for the "net" amount of electricity used—the amount greater than what the facility generated. As of 2013, 43 states plus the District of Columbia had net metering policies in place (*38*).

Net metering agreements rely on the utility to establish an interconnection between the facility and the grid in order to provide the utility access to the electricity generated. Interconnection policies and procedures are largely driven by the utility companies themselves, under the guidance of CPUC. Electric Rule 21 governs interconnections under CPUC jurisdiction, including all net metering facilities, and establishes a tariff for customers wishing to connect their energy-generating facility with the grid (*59*). As a result of Rule 21, each major utility keeps its own version of the tariff, which guides the process for customers to safely and reliably connect with the distribution and transmission systems.

Section 2827(c)(1) specifies that the net energy metering (NEM) tariff must be available to eligible customer-generators upon request on a first-come, first-served basis until the total rated generating capacity used by eligible customers exceeds 5 percent of the electric utility's aggregate customer peak demand, or until July 1, 2017, whichever is earlier, and further defines minimum program limits for the three major electric utilities in California (SDG&E, SCE, and PG&E) (*73*). These initial tariffs are sometimes referred to as NEM1.

Section 2827.1 defines the rules for NEM2, the tariffs that became available for eligible customers once net metering limits described under Section 2827 were reached, or beginning July 1, 2017, whichever occurred earlier (*74*). Under Section 2827.1, there are no time or capacity limits for eligible customers to receive the standard contract tariff starting July 1, 2017. In addition, generator size is no longer limited to 1 MW or smaller, which means the generator can be sized to meet the owner's annual load.

Net Energy Metering Sub-schedules

There are several variations of the NEM and NEM2 electric schedules, called sub-schedules, which vary slightly by the utility that implemented the schedule. For example, PG&E has the following NEM2 sub-schedules, many of which apply to special conditions described in detail in the schedule (*75*):

- NEM2S, for small customers as defined in Rule 1 with renewable facilities generating 30 kW or less.
- NEM2EXP, for small customers as defined in Rule 1 with renewable facilities generating 1,000 kW or less, other than facilities generating 30 kW or less.
- NEM2EXPM, for all other customers generating power under Special Condition 2.
- NEM2MT, for customers generating power in a multiple tariff facility under Special Condition 4.
- NEM2A, for customers generating power under a load aggregation arrangement described in Special Condition 6.
- NEM2ACDCR, for energy generation by the California Department of Corrections and Rehabilitation described in Special Condition 7.

In addition to these sub-schedules, other tariffs might be available from a utility, such as Virtual Net Energy Metering (VNEM), Renewable Energy Self-Generation Bill Credit Transfer (RES-BCT), and NEM Fuel Cell (NEMFC) (*76*). Of the sub-schedules listed above, net energy metering aggregation might be of further interest and is described in more detail in the following section.

Net Energy Metering Aggregation

In general, net energy metering aggregation, or load aggregation, under the tariff starting July 1, 2017 (NEM2A), allows a customer with multiple meters on the same property or on adjacent or contiguous properties to user renewable energy sources to serve the aggregated load behind all program-eligible meters and receive the benefits of NEM2 (*77*). According to the California Public Utilities Code, eligible customers that aggregate electric generation under NEM2A are permanently ineligible to receive net surplus electricity compensation, and the electric utility retains all electricity generated in excess of the customer's electrical load generated during each 12-month period (*78*). In addition, net metering aggregation is limited to renewable-energy-generating facilities with a total generating capacity of not more than 1 MW (*79*).

Power Purchase Agreements

Public agencies in the United States, including California, have considered interconnection of utility-scale solar energy facilities in public right-of-way to the regional utility grid using power purchase agreements (PPAs) (*72*). These agreements involve a developer that installs and operates the solar facility on land owned by another entity and sells the generated electricity to a partnering utility. The developer is the third party in addition to the utility and the public agency, which is the reason that PPAs are sometimes referred to as "third-party PPAs." A solar PPA is defined by the Solar Energy Industries Association and referenced by Caltrans as follows:

> A PPA is a financial agreement where a developer arranges for the design, permitting, financing and installation of a solar energy system on a customer's property at little to no cost. The developer sells the power generated to the host customer at a fixed rate that is typically lower than the local utility's retail rate. This lower electricity price serves to offset the customer's purchase of electricity from the grid while the developer receives the income from these sales of electricity as well as any tax credits and other incentives generated from the system. PPAs typically range from 10 to 25 years and the developer remains responsible for the operation and maintenance of the system for the duration of the agreement. At the end of the PPA contract term, a customer may be able to extend the PPA, have the developer remove the system or choose to buy the solar energy system from the developer. (*80*)

Third-party solar PPAs are allowed in 25 states plus the District of Columbia, not allowed in 11 states, and have an unknown or unclear status in 14 states, as follows (*81*).

- **States that allow PPAs:** Arizona, California, Colorado, Connecticut, Delaware, Georgia, Hawaii, Illinois, Iowa, Maine, Maryland, Massachusetts, Michigan, Nevada (limited), New Hampshire, New Jersey, New Mexico (limited), New York, Ohio, Oregon, Pennsylvania, Texas, Utah, Vermont, Virginia (limited), District of Columbia.

- **States that do not allow PPAs:** Alabama, Alaska, Arkansas, Florida, Idaho, Kansas, Kentucky, North Carolina, Oklahoma, South Carolina, West Virginia (restricted).

- **States where the status of PPAs is unknown or unclear:** Indiana, Louisiana, Minnesota, Mississippi, Missouri, Montana, Nebraska, North Dakota, Rhode Island, South Dakota, Tennessee, Washington, Wisconsin, Wyoming.

Williamson Act Program

The California Land Conservation Act, or the Williamson Act, was intended to protect agricultural and open-space land at a time of increasing development (*82*). Currently, the Williamson Act Program allows local governments to enter into a contract with private owners to restrict certain parcels of land for agricultural or open-space purposes. The property owner is then eligible for a substantial reduction in his or her property tax assessment. The property tax assessments are based on generated income rather than the potential market value of the property (*82*). Benefiting from the Williamson Act Program generally prohibits a landowner from installing solar facilities on the land since this is not an agricultural use.

LOCAL GUIDANCE

Local ordinances provide guidance on the zoning and placement of solar systems within the city or county limits. If Caltrans needs additional land outside of the right-of-way to install, manage, or maintain facilities, then local ordinances and regulations may need to be followed. In California, a number of localities have addressed the installation and placement of solar facilities to meet their climate goals and to allow for the repurposing of land. The majority of local ordinances relate to small-scale solar facilities that individual customers or businesses may want to place on their houses or existing infrastructure. The following guidance details local ordinances in relation to commercial or utility-scale solar installations. These larger-scale installations are often subject to more extensive permitting guidelines and review and approval processes. Some cities or counties restrict the placement of these facilities to certain zoning types, such as agricultural districts. Local issues and ordinances can provide some guidance on the overall legal environment surrounding solar installations that may help inform statewide policies.

Placement, Permitting, and Zoning

The City of Lancaster restricts the placement of solar farms, which are larger solar facility installations as opposed to photovoltaic panel system roof installations. These installations are limited to land that is zoned as "rural residential." However, the smaller solar energy systems can be placed anywhere within city limits (*83*).

The City of Irvine altered its municipal code to promote the installation and use of solar energy systems (*84*). However, in terms of commercial, industrial, institutional, office, or multiuse applications, only rooftop and parking cover systems are specified. The code does not discuss larger-scale solar installations.

Butte County limits the installation of intermediate and major utility-scale solar systems to agricultural land that has been designated as grazing land or "other land." The land also cannot be subject to the Williamson Act Contract that conserves farmland (*85*).

Kern County allows solar energy systems under the majority of its zoning codes, but there are restrictions due to size. Larger facilities, defined as those that are not considered accessory and will generate more electricity than the property demands, are often only conditionally permitted in most zones. The county ordinances specifically allow for commercial facilities in natural resource, light industrial, recreational forestry, and platted land districts.

San Bernardino County restricts renewable-energy-generating facilities to 12 zoning codes that are primarily agricultural or commercial in nature (*86*). Commercial solar installations must meet an additional set of requirements that ensures the facility is considered desirable to the communities located within the county. Once those conditions are met, the developer of a solar energy facility must acquire a special-use permit that is renewed annually (*87*).

Santa Clara County has separate regulations for solar energy systems that are deemed commercial as opposed to those that primarily provide power to a residential or agricultural property. Minor commercial solar energy systems cover 8 acres of land or less and are no taller than 35 feet. Any facility larger than these specifications, including multiple facilities that would cover more land, are considered major commercial solar energy systems (*88*). All major systems require a use permit that includes architectural and site approval in rural base districts. However, minor systems just require architectural and site approval depending on the zoning code of the land (*89*). Solar energy systems are permitted in general-use special-purpose districts as well; minor systems require just architectural and site approval, but major systems require a use permit (*90*). The general-use code under special districts is intended to be a flexible zoning code to accommodate unique developments, such as solar energy systems. Solar energy systems are prohibited in certain agricultural districts and design review combining districts (*91*).

Yolo County differentiates between large and very large solar systems (*92*). However, both require a major-use permit from the County Board of Supervisors before a facility can be installed. Large solar systems are defined as a utility-scale solar energy conversion system that consists of ground-mounted solar arrays in rows and is "occupying more than 30 acres and no more than 120 acres of land, and that will be used to produce utility power to off-site customers." Very large solar systems cover more than 120 acres of land and produce utility power for off-site customers.

Large solar systems can be placed in the following zoning classifications: "agricultural districts (the Agricultural Intensive (AN) zone, the Agricultural Extensive (A-X) zone, and the Agricultural Industrial (A-I) zone); public and open space districts (the Public Open Space (POS), Park and Recreation (P-R), and Public Quasi-Public (PQP) zones); and industrial districts (the Heavy industrial (I-H) and the Light Industrial (I-L) zones)." Very large solar systems are restricted to agricultural districts and the A-I zone (*92*).

All of the local codes and ordinances discussed also mention the Williamson Act, which restricts the conversion of farm land to another use if the owner has applied for property tax relief through this act (*93*). Land that is subject to these provisions must follow the rules set forth in California Government Code Section 51238.1, or the local ordinance will specifically prohibit the installation of solar facilities on this land.

FUNDING MECHANISMS

Several mechanisms support the funding of renewable energy installations, including federal tax credits, corporate depreciation, grants and loans, and the CREB Program (*94*).

- **Financial Federal Tax Credits.** The Business Energy Investment Tax Credit provides a tax credit for a percentage of expenditures on eligible renewable technologies. The percentage is planned to be decreased in coming years. The Renewable Electricity Production Tax Credit is a per-kilowatt-hour tax credit for electricity generated by qualified energy sources constructed before December 2019.

- **Corporate Depreciation.** Instituted in 1986, the federal Modified Accelerated Cost-Recovery System (MACRS) creates a method of depreciation that allows businesses to recover investments in certain property through annual deductions. Under MACRS, solar energy equipment is eligible for a cost-recovery period of five years.

- **Grants and Loans**. The U.S. Department of Energy and the Department of Agriculture have a number of grant programs for renewable energy. The technologies that are eligible and the allowable funding amounts vary by program.

- **Clean Renewable Energy Bond Program.** California Streets and Highways Code Section 157.8 mandates that Caltrans report annually on the issuance of CREBs (*95*). These bonds are used to finance "the acquisition and installation of photovoltaic (solar) energy systems until maturity of the bonds" in fiscal year 2024 (*95*). There have been 70 projects funded and constructed under the CREB Program. Caltrans monitors 61 sites and is estimated to save approximately $2.8 million over the life of the facilities.

- **Emissions Trading Program.** The California Air Resources Board Emissions Trading Program sets a statewide limit on sources responsible for 85 percent of California's greenhouse gas emissions to encourage long-term investment in cleaner fuels and reduce emissions (*96*).

- **Renewable Energy Credits (RECs)**. RECs were established by the California Legislature as part of the California Renewables Portfolio Standard Program (*97*). The California Public Utilities Code defines an REC as a certificate that provides proof of one unit of electricity generation from a renewable resource.

- **Climate Catalyst Fund.** The California Legislature planned to introduce a $1 billion revolving loan program in the 2020/2021 state budget to seed recycling, low carbon transportation, and climate-smart agriculture projects. Revisions to the budget proposal first reduced the program to $250 million, and as of May 14, 2020, the proposed fund has been withdrawn from consideration (*98*).

Note that the deliverable for Task 6 provides an in-depth analysis of funding opportunities and financing strategies.

CONCLUSIONS

From a regulatory perspective, the use of state right-of-way by a solar facility depends on whether or not the facility is considered a utility. Federal guidance provides two procedures, which differ based on the state's definition of a utility. The State of California includes renewable energy facilities within its definition of a utility, so as long as the renewable energy facility is owned and operated by a utility that provides energy directly to the public or consumer, 23 CFR Part 645 and California's UARs apply. Otherwise, the renewable energy facility requires an agreement for use of the right-of-way by the private entity, with a fee assessed based on fair market value subject to 23 CFR 710 and the rules contained in 23 CFR 771.

In situations where the renewable energy facility is owned and operated by an entity other than a utility, a PPA and/or net metering agreement will be required. Since the facility will not be owned by Caltrans or a utility, there will also be a need for a right-of-way use agreement. PPAs allow a developer to take on the financial burden of designing, building, and operating the facility, and in return, the developer sells the generated electricity to the host customer. If Caltrans desires to place a solar facility in the right-of-way but not maintain ownership or operate the facility, a PPA is required. In order to connect to the regional electric grid, the operator of a solar facility requires an interconnection; these are generally managed by the local utility that also sets standards under the guidance of Electric Rule 21. NEM agreements are required with an interconnection to manage the exchange of electricity between the facility owner/operator and the electric utility. These agreements establish billing standards and ensure the generator of the energy receives credit or payment at the retail value of the electricity less any energy used by the owner/operator. A sub-schedule of the current net energy metering schedule NEM2 that allows for net energy metering aggregation (NEM2A) might be of interest to Caltrans. This sub-schedule allows for the aggregation of the electricity generated under several meters owned by a single customer with contiguous, adjacent properties. However, as written, this sub-schedule does not allow any electricity production over 1 MW in total and does not allow the sale of electricity back to the utility that was generated in excess of the amount that is used at the site.

Utility companies are incentivized to enter into agreements that provide renewable electricity generation or to generate their own renewable electricity through the RPS and attached goals. The RPS mandates that a certain percentage of energy be generated from renewable sources. In addition, financial incentives, such as tax credits, are available to eligible businesses. Possible incentives for Caltrans are also available through federal loan and grant programs and the ability to leverage clean energy bonds.

In general, the main barriers to utility-scale projects surround interconnection and net metering rules and agreements; these will often differ by utility company, which could lead to a patchwork of regulations. Current state legislation has largely been aimed at regulating residential solar facilities and ensuring their fair, safe, and reliable access to the grid through the utility companies. This legislation, in some instances, restricts the ability of entities to install solar facilities that aim to generate a large amount of electricity; however, that may not have been the original intent of the legislation. The utility-scale or non-residential solar market in the United States is still relatively small; nonetheless, these facilities generate far more electricity per installation than residential installations. Currently, most utility-scale projects are completed by a utility, which eliminates the need for net metering and interconnection agreements. As the non-residential solar market grows, there is potential for additional rules and regulations regarding these installations.

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APPENDIX D: FINANCIAL OPPORTUNITIES ASSESSMENT

Caltrans Project No. P1253
Caltrans Task No. 3177

Solar Power Initiative Using Caltrans Right-of-Way

Financial Opportunities Assessment

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Submitted to

DIVISION OF RESEARCH, INNOVATION, AND SYSTEM INFORMATION

CALIFORNIA DEPARTMENT OF TRANSPORTATION

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Contents

Introduction

This report is intended to provide commercial insights into various commercial structures, contractual relationships, and financing arrangements that might be utilized in the development, operation and maintenance of commercial and utility scale solar photovoltaic (PV) projects within Caltrans' right-of-way. These arrangements are also compared against more traditional power purchase agreements (PPAs) with local power utilities. There are numerous commercial structure options that can be utilized with a third-party private partner involved to develop, deliver, finance and operate solar PV projects. Depending on the requirements of Caltrans and the ownership interests of additional power off-takers and lessors, unique arrangements can be created to suit the needs of each participating party.

Before determining the best project development and delivery model for solar projects, it is critical for Caltrans to first evaluate the costs, initial capital, as well as lifecycle, operations and maintenance, for different models of power procurement. Each power supply model has varied benefits depending on the anticipated load, existing legislation, costs, generation locations, and transmission and distribution requirements. This report is broken into three major models of energy procurement and project delivery including self-ownership, public-private-partnership, and traditional PPAs.

Below is a summary of ownership and development models as well as funding and financing types. Each of these are further detailed throughout the report.

Ownership and Project Development Model Summaries

Third-Party PPA (P3)	Contractual arrangement with a private entity to design, build, finance, operate and maintain (or any combination thereof) a solar project with little to no upfront capital investment required by Caltrans
Morris Model (P3)	A hybrid PPA and bond issuance model where a private developer designs, builds, operates and maintains (or any combination thereof) a project with Caltrans and the Department of Treasury provides low rate financing
Direct Access (Traditional PPA)	PPA with an electricity service provider as opposed to a utility, potentially offering lower power pricing
Community Choice Aggregation (Traditional PPA)	Power procured from an alternative supplier, while transmission and distribution services are provided by the local utility

Funding and Financing Summaries

Types	Description
Appropriated Funds	Funding directly appropriated to Caltrans
Financing Against Caltrans' and State of California Funds	Funding outside that which is appropriated to Caltrans including the State Highway Account, Senate Bill 1 (Rebuilding California), and others
Climate Resilience Bond	Proposed financing measure in the Governor's 2021 budget
Climate Catalyst Fund	Proposed financing measure in the Governor's 2021 budget
Cap-and-Trade Funds	Funding through the California Air Resources Board earmarked to reduce emissions from transportation, among other items
Lease Revenue Bonds	Bonds structured around a loan made to the State that is repaid by income generated by an infrastructure project
Garvee Bonds	Bonds that utilize funds borrowed against future anticipated federal grants in order to develop a project at present. Solar projects may not qualify.
Private Capital	A private enterprise providing equity or debt financing
Project Revenues	Monies received from a land lease agreement or sale of electricity

Ownership and Project Development Models

Self-Ownership

One of the most basic approaches to developing solar PV would be for Caltrans to self-fund and own solar power systems within its right of ways. Caltrans could issue a Request for Proposal (RFP) for a private company to design and build the project to Caltrans' requested size and siting (Note: Caltrans' could develop in-house skills to design solar projects leveraging existing engineering capabilities, potentially through the Professional Engineers in California Government union. If considered, Caltrans should thoroughly examine the efficiency of project development and delivery, in addition to costs, compared to leveraging the capabilities of a specialized private firm). A separate contract could be awarded to support the maintenance requirements of the solar arrays and system components. In this scenario, Caltrans would bear the financial burden for the entire project, both initial capital costs and lifecycle operations and maintenance. While certain guarantees could be built into the design, build, operation and maintenance contracts, Caltrans would also generally bear the long-term risk associated with the project. Caltrans would be free to consume all of the power generated, or sell to other consumers, subject to analysis regarding net metering regulations and legislative authority.

Potential benefits to Caltrans include the ability to maintain full control over project design, development and operations, and properly manage all risks. Further, Caltrans would have the ability to choose what to do with the renewable energy attributes generated by the project (retain or monetize).

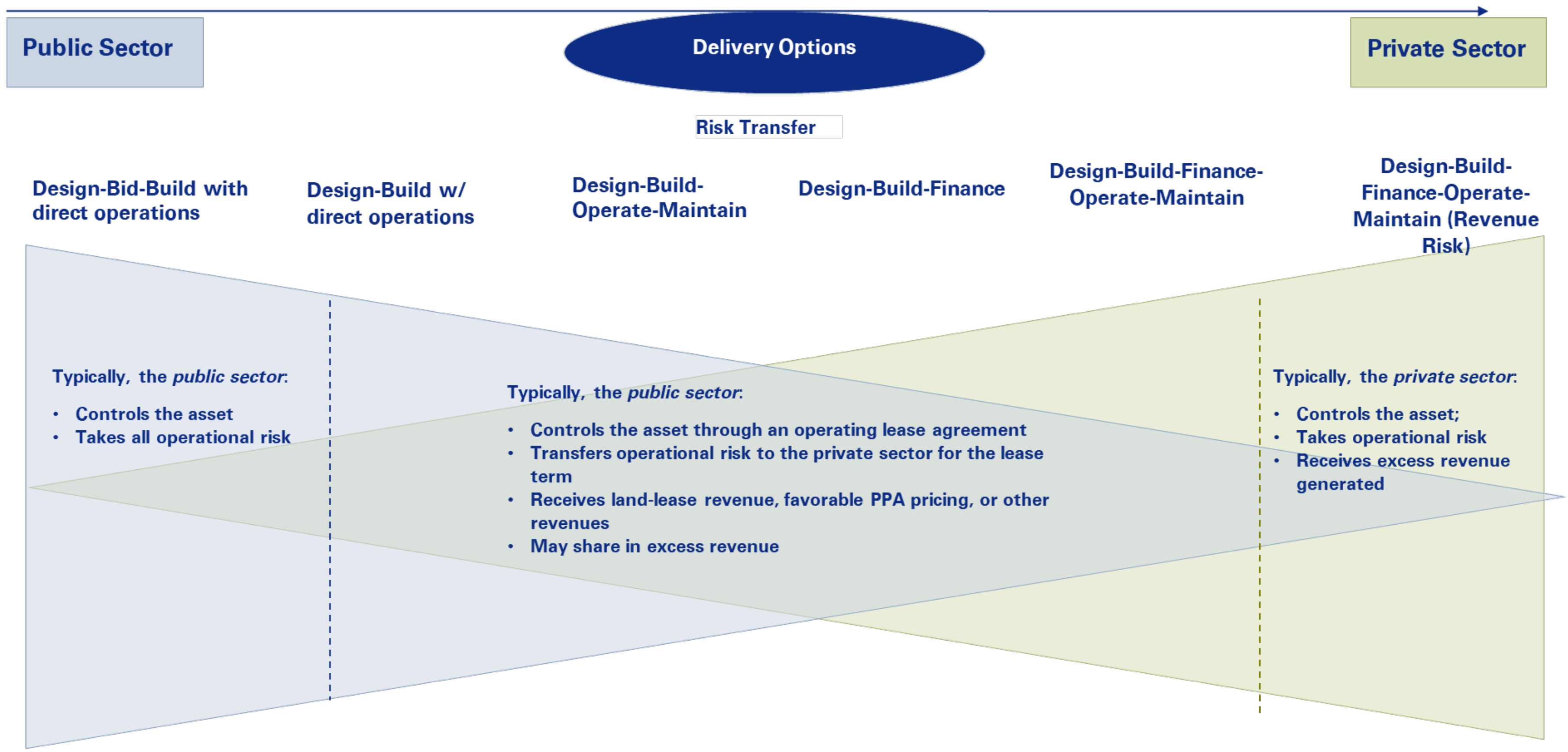
One of the greatest challenges to Caltrans would be the need to augment staff technical knowledge and capabilities as this would be a relatively new type of project for the Department. Further, as a public entity, Caltrans would be unable to utilize state and federal renewable energy tax incentives which private parties can leverage. Obtaining the required capital may also be a challenge, whether through appropriations by the State or in collaboration with the State Treasurer's Office for a bond issuance.

Public-Private Partnership (P3)

A P3 involves a partnership between the public and private sector to share the risk and rewards of constructing, financing, operating, and/or maintaining what are traditionally publicly owned assets in order for projects to be completed at an enhanced value-for-money (VfM) to the public sector owner. In a P3, the private sector is often engaged to help design, deliver, finance, operate and maintain (or any combination thereof) infrastructure, community facilities, or other services for a fixed period of time. Private sector capital (debt and equity) can be used to develop the project, with no upfront capital required from Caltrans, with investments recovered over the life of the contract. For renewable energy projects specifically, the private sector can monetize tax incentives which are otherwise unavailable to government organizations. These incentives can help to lower the project's lifecycle cost to the private party with the potential for savings being passed to the public entity. Several state Departments of Transportation, including Massachusetts, Oregon, and Georgia, have already developed solar initiatives in their right of ways through a P3 mechanism.

When considering a P3 procurement versus self-ownership and development, it is important to analyze the VfM. VfM is one step in a project delivery model evaluation which takes inputs from a preliminary delivery model assessment (considering agency objectives, sources of funding, project prioritization, organizational capacity, governance, and other metrics) and risk analysis (analysis of risk allocation between traditional delivery and P3 including what risks can be transferred to a developer, possibly resulting in cost savings). These evaluations will provide inputs to the VfM analysis. Under a VfM analysis, two independent financial models are built (public sector comparator and shadow bid model) in order to quantify the overall delivery costs of traditional delivery and the selected alternative delivery method. The difference in costs between traditional and alternative delivery is the VfM differential. The VfM analysis can help to assess the value that a P3 could provide, comparing it with more traditional project delivery means. It helps demonstrate to stakeholders if there are clear benefits that outweigh the associated costs or risks of private-sector participation. This also allows public entities to optimize project delivery and provide transparency to taxpayers regarding their considerations of infrastructure investments.

The image below depicts the range of P3 delivery options which could be structured for a project's development, portraying risk transfer to the private partner. Subsequently, below the image, three specific contracting and finance structures are explained which could leverage the private sector's expertise through a P3.


Public Sector
Delivery Options
Private Sector
Risk Transfer
Design-Bid-Build with direct operations
Design-Build w/ direct operations
Design-Build-Operate-Maintain
Design-Build-Finance
Design-Build-Finance-Operate-Maintain
Design-Build-Finance-Operate-Maintain (Revenue Risk)
Typically, the public sector:
Controls the asset
Takes all operational risk
Typically, the public sector:
Controls the asset through an operating lease agreement
Transfers operational risk to the private sector for the lease term
Receives land-lease revenue, favorable PPA pricing, or other revenues
May share in excess revenue
Typically, the private sector:
Controls the asset;
Takes operational risk
Receives excess revenue generated

Third-Party PPA (non-utility)

Caltrans could contract directly with a private entity to design, finance, construct, operate and maintain (or some combination thereof) the solar project within its right of way. Caltrans would negotiate a PPA directly with the private entity and purchase some or all of the power which was produced. Depending on the contractual arrangement, excess power generated could be sold to the local electric utility or other off-takers, with a portion of the revenues flowing back to Caltrans. Alternatively, Caltrans could receive favorable power pricing in exchange for the private developer being able to sell excess power to third parties.

Under this structure, Caltrans would benefit from being required to provide little to no upfront capital investments. Caltrans would enter into a PPA for fixed electricity prices for 10-20 years, at a rate potentially lower than the local utility. Caltrans would face no operating or maintenance responsibilities, but could have rights to buy the project at the end of the contract term. Further, the private developer could leverage federal tax incentives which could yield savings to Caltrans. Finally, the private developer may be able to deliver the project more quickly, at a lower cost, and integrate newer and more efficient technologies throughout the lifecycle.

Challenges to Caltrans may include a complicated and lengthy procurement and negotiation process for the P3 contract and PPA, including both contractual and union negotiations. Caltrans may also have limited control over the project's design, operations and risks. Depending on the negotiation, the PPA pricing could be sub-optimal with the developer retaining most of the financial and tax benefits. Finally, if the PPA term is less than the useful life of the PV system, Caltrans may be required to purchase the assets at fair market value at the end of the term, resulting in Caltrans being responsible for maintaining and operating the asset, and, ultimately, disposing of the asset, possibly by contracting for those services.

Solar Lease / License Revenue[1]

Caltrans could lease a portion of land within the right of way to a private developer who would wholly develop solar PV facilities. Depending on the arrangement with the developer, Caltrans could have multiple options in structuring the contract. Several options include:

1. Caltrans receives only land lease payments from the private developer, but purchases no electricity in the transaction. The developer is free to sell power to the local utility, or other commercial and industrial off-takers. In this structure, Caltrans would not commit to consuming the power while still benefiting from fixed land lease payments.
2. Caltrans could pay the developer an Availability Payment for the PV facility to be operational, and consume all electricity generated. Caltrans would pay for the use of the solar facility over a specified period of time, rather than paying for the power being generated. This model is similar to the third party PPA model above.
3. The private developer would develop a large PV system generating more electricity than required by Caltrans. The developer would sell the majority of power to third-parties (local

[1] Caltrans Senior Right of Way Agent Resham Haddox notes that fair market lease rates must be charged and must also conform to the California Transportation Commission's (CTC) G-02-14 resolution. FHWA approval must also be sought. Task 4 of this engagement "Summary of Rules and Regulations" provides further analysis into the topic.

utility or other off takers) but offer Caltrans reduced power prices in exchange for the use of its land.

Similar to the third-party PPA model above, these structures may be beneficial to Caltrans in that they require little to no upfront capital investments from the Department. Caltrans would face no operating or maintenance costs, and the private developer could leverage federal tax incentives which could yield savings to Caltrans. Further, Caltrans may be able to benefit from lower power prices, or receive additional revenues through airspace lease agreements.

These development structures may include a complicated and lengthy procurement and negotiation process. There may also be restrictions that Caltrans faces regarding the use and monetization of its land which would require further investigation and coordination with the State Treasurer's Office, Federal Highway Administration (FHWA) and legal analysis.

Morris Model (Hybrid Bond-PPA) [2]

This model has been studied by the U.S. Department of Energy's National Renewable Energy Laboratory as an innovative model to finance Solar PV at government sites. The hybrid model leverages the use of low rate financing obtained from a government issued bond in exchange for a lower PPA price from the private developer. In practice, Caltrans would issue an RFP seeking a private solar developer to build, operate and own a solar project or portfolio of projects on Caltrans buildings, lands and right-of-way. Caltrans would work with the California State Treasurer's Office to sell bonds to finance the development costs of the solar installation. Caltrans then enters into both a lease-purchase agreement and PPA with the private developer to buy electricity from the PV system. While the bond may be taxable if the project is owned by a private solar developer, the good credit rating of Caltrans and the State of California would often make the borrowing rate less than the solar developer could obtain on its own. The solar developer would make lease payments to Caltrans that fully cover the bond payments, with these lease payments being lower than the loan payments on funds that the solar developer would have otherwise borrowed. These cost savings mean that the solar developer can offer Caltrans an attractive PPA price while still making strong financial returns. This model was first implemented in Morris County, New Jersey, but other examples include the City of Denver providing low-interest capital (raised through appropriations) to a developer to build two Denver International Airport solar projects.

The benefits to this hybrid model are similar to that of the Private Party PPA noted above, but the benefits are improved in that Caltrans and the State Treasurer's Office are able to provide low-cost capital to the project. By providing capital and assuming financial risk, the public entity has lowered the project's costs and therefore can negotiate improved PPA terms.

The challenges to this model for Caltrans may be the higher transaction costs due to the novelty of approach for the Department, as well as both costs associated with a bond issuance and PPA negotiations. The bond issuance will also pose a challenge as Caltrans would need to work through the California State Treasurer's Office, identifying a clear revenue stream without violating the Department's

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[2] Caltrans Senior Right of Way Agent Resham Haddox notes that fair market lease rates must be charged and must also conform to the California Transportation Commission's (CTC) G-02-14 resolution. FHWA approval must also be sought. Task 4 of this engagement "Summary of Rules and Regulations" provides further analysis into the topic.

mandate and legislative restrictions. Any consideration of seeking a bond issuance should undergo legal review.

Traditional PPA

The traditional PPA model aligns with the current method of power procurement by Caltrans. More broadly defined, a PPA is a contract between two parties, one of whom generates or sells electricity, and one of whom is purchasing electricity. The most common PPA is entered into with a utility, such as Pacific Gas & Electric Company in Caltrans' Northern California territory. There are multiple PPA contractual arrangements which exist and could be beneficial to Caltrans, depending on the Department's ultimate goal. Below are four PPA models:

Utility Contract

This is a standard contract with the local electric utility to purchase power at established rates. Utilities generally provide the option to buy solar and/or renewable energy specifically which would be administered by the utility. Depending on the quantity of power being purchased, some utilities offer discounts on their electricity tariffs.

Direct Access

Direct Access is a model where Caltrans could purchase power from an Electricity Service Provider (ESP), in line with California Public Utility Commission (CPUC) regulations. Public Utilities Code Section 394 defines an Electric Service Provider (ESP) as a non-utility entity that offers electric service to customers within the service territory of an electric utility. A list of ESPs is provided on the CPUC website (https://apps.cpuc.ca.gov/apex/f?p=511:1:0::NO:::)

An ESP would generate or aggregate the electricity, and it will be supplied through the local utility's transmission and distribution system. Direct Access is typically utilized by medium to large commercial and industrial customers, but Caltrans may consider pursuing the option. Direct Access allows a deregulated market to be simulated through more competitive pricing than a regulated utility would offer.

Regional Renewables Choice / Community Choice Solar

Caltrans may be able to subscribe to a single renewable energy project via a direct contract with a developer. Once the project becomes operational, the renewable developer invoices the purchasing party, such as Caltrans, for their portion of the power which the project generates. Caltrans would maintain its PPA contract with the local utility, but would provide a credit on its monthly electric bill for the subscribed power. Power not received from the private developer will be provided by the electric utility.

Community Choice Aggregation

A community of residents, businesses and municipal accounts could aggregate their demand to purchase power from an alternative generator, while still receiving transmission and distribution services from the existing utility provider. This allows more control over generation sources and often lower electricity prices. By aggregating demand, communities or large organizations gain leverage to negotiate better rates with competitive suppliers and choose greener power sources.

Types of Funding and Financing Available

Caltrans may have access to various funding streams and financing opportunities to utilize in the development of solar PV projects. When considering how to pay for projects, it is first important to understand the differences between funding and financing. Funding is monies provided by the government or other entities that does not have to be repaid – likely sourced from taxation, fees, donations or other public sources. Financing is monies provided by a lender that must be repaid over a specified term, with a specified interest rate and other conditions attached. Financing generally requires an identified revenue stream in order to repay the monies. Below is a description of some options that Caltrans may consider, subject to further analysis:

Appropriated Funds

Caltrans could utilize funds directly appropriated, or request additional appropriated funds specific to the development of solar PV in future fiscal years.

Financing Against Caltrans' and State of California Funds

Article 19 of the California Constitution prohibits borrowing against the state highway account. However, Caltrans should explore precedents where they have previously borrowed against this account (lease of buildings or other assets) which could be replicated. Alternatively, Caltrans should investigate whether this prohibition also applies to State Bill 1 (Rebuilding California) monies. Separately and subject to a legal analysis, state general funds, state highway account monies, or SB1 monies could pay for an operating lease or PPA.

Climate Resilience Bond

California Governor Newsom has proposed a $4.75 billion climate resilience bond, to be approved by voters, which would provide for investments that reduce risks from water, fire, extreme heat and sea level rise. Caltrans would have to investigate whether their projects could qualify for this financing which would be raised through the bond.

Climate Catalyst Fund

California Governor Newsom has proposed a four-year one-billion dollar revolving low-interest loan program to seed recycling, low-carbon transportation, and sustainable smart agriculture projects. Caltrans would have to investigate whether their projects could qualify for these loans.

Cap-and Trade Funds

California Air Resources Board permits the use of money raised from California's cap-and-trade program for reducing emissions from transportation. Caltrans would have to investigate whether their projects could qualify for these funds.

Lease Revenue Bonds

Subject to appropriation and approval by the State Treasurer's Office, Caltrans could utilize lease revenue bonds. These bonds are structured around a loan made to the State that is repaid by income generated by the solar project.

Garvee Bonds

In collaboration with the California State Treasurer's Office, Caltrans could consider utilizing Garvee bonds. These bonds utilize funds borrowed against future anticipated federal grants in order to develop a project at present. The tenure of Garvees is 12-15 years, comporting well with the average life of solar installations. Solar projects may not qualify but should be investigated against precedent projects across the country.

Private Capital

If partnering with a private company to develop the project, it could be required that this private entity bring its own financing to the project. This would include a mix of private equity and debt. While Caltrans may not incur any upfront costs to develop the project due to the private capital investments, they may be required to pay a monthly recurring fee or sign a PPA depending on the contractual arrangement.

Project Revenues

Depending on the development model pursued, Caltrans may be able to earn revenues from the project (e.g. land lease or electricity sales). These revenues could be used to repay bonds or other financing utilized for the project's development.

Additional Financial Tools

Investment Tax Credit (ITC)

The Federal ITC was established to increase private sector investments in solar manufacturing and solar project developments. The ITC allows an equity owner of a qualifying renewable energy asset to claim an income tax credit equal to a percentage of the value of the asset's eligible basis. Solar PV projects installed before December 31, 2019 received a 30% credit; between January 1-December 31, 2020 receives 26%; between January 1-December 31, 2021 receives 22%; and January 1-December 31, 2022 receives 10%. After January 1, 2023, tax credits would continue at a rate of 10% for utility and commercial projects. While Caltrans is unable to directly leverage this tool, they could investigate partnership with a private party to yield shared savings.

Tax Equity Financing

When private solar project developers, sponsors and owners don't have enough taxable income to take advantage of the ITC benefits, some financial institutions and corporations with significant federal tax burdens invest in solar projects as equity owners. This provides additional project capital while allowing the third-party equity investor to utilize the ITC tax benefits. Caltrans should conduct a legal analysis to determine if they could directly leverage this tool with private investment. Alternatively, this tool could be leveraged by a private developer should Caltrans consider a P3 development model.

Additional Tools and Incentives

There are additional tax advantages and incentives which could be leveraged when developing solar projects, particularly when engaging a private partner. The Database of State Incentives for Renewables & Efficiency (DSIRE) provides list of California available incentives, however, Caltrans should note that many of these are specific to residential and commercial installations, and may not be available to a government entity. Additional incentives may be unlocked if engaging a private party, such as their ability to depreciate the asset and write-off these depreciation expenses.

Precedent Market Examples of DOT Solar Projects

This section provides an overview of select precedent projects in the U.S. where a transit department has leveraged its right of way to develop solar projects. It is important to note that many of these projects are nearly 10 years old, and historical costs are not representative of anticipated current costs. Due to increased manufacturing of solar panels and efficiency improvements, current solar costs are **much lower** than a decade past.

Massachusetts Department of Transportation

In 2012, the Massachusetts Department of Transportation (MassDOT) began exploring the potential of solar developments within its right of way by identifying approximately 60 sites that could be used for solar generation. In 2014, they awarded a contract for the development of 6 MW of solar, across multiple sites, along the right of way. Most of the projects are located along the Massachusetts Turnpike (1-90) with one site located on Route 3 in Plymouth.

MassDOT leveraged a P3 development structure with no upfront funding from the State being required. MassDOT leased the sites to the private developer for 20 years and agreed to purchase all of the electricity generated through a PPA. The developer was able to leverage State renewable energy credits and Federal tax incentives. As of 2018, the projects have produced 10,750 MWh of electricity and have yielded net savings to MassDOT of more than $1 million. The expected savings are approximately $525,000 annually, in addition to the $75,000 land-lease payments for the sites.

Ohio Department of Transportation

In 2010, the Ohio Department of Transportation (ODOT) developed solar within the right of way of Interstate 280, near Toledo. The solar array occupies four acres, generating electricity to offset the power used by the lighted pylon of the Veteran's Glass City Skyway. ODOT owns the project, and partnered with the University of Toledo to create the state's first large-scale solar array on a highway right of way. The project cost an estimated $1.5 million to develop, with an additional $500,000 in pre-development analysis. ODOT leveraged a federal grant of $1.5 million to fund the project.

Oregon Department of Transportation

In 2008, Oregon Department of Transportation (Oregon DOT) developed a 104-kW solar pilot project at the intersection of Interstates 5 and 205. This $1.28 million project was developed through a partnership between Oregon DOT and the utility, Portland General Electric. Funding was provided by the Energy Trust of Oregon. The project developer was able to leverage a 50-percent State tax credit for renewable energy projects, in addition to a 30-percent Federal tax credit for the solar investment. Portland General Electric, along with the tax equity partner Energy Trust of Oregon, formed a limited liability company that could use the tax credits and other incentives. All of the renewable energy certificates generated went to the Energy Trust of Oregon in exchange for grant funding that helped bring the cost of energy down to market rates. Oregon DOT entered into a PPA to buy all electricity produced at the same rate as traditional grid power.

In 2012, Oregon DOT and Portland General Electric pursued a larger 1.75 MW project at the northbound Interstate-5 Baldock Safety Rest Area, approximately 7 miles south of the first project. The Baldock project cost $10M to develop and again, Oregon DOT and Portland General Electric partnered for the project's development. The development structure was known as a sale, lease-back contract. Portland General Electric financed and constructed the project, and sold it upon completion to a tax equity partner, which then leased back to the utility to operate and maintain. Oregon DOT receives a small annual site lease fee, and a percentage of the renewable energy certificates generated throughout the life of the project.

Denver International Airport

Denver International Airport (DIA), owned by the city and county of Denver, has installed a 2 MW solar array to provide up to half of the electricity required to power the airport's people mover transit system. DIA entered into a third-party long-term PPA with MMA Renewable Ventures, a private entity that financed and owns the project. The 25-year PPA was fixed price at 6 cents/kWh for the first 5 years, with a buyout option at the beginning of year 6 or price increases to 10.5 cents/kWh. MMA Renewable Ventures has monetized the Renewable Energy Credits earned from the project by selling to Xcel Energy to help it fulfill its state renewable energy obligation by 2020. MMA Renewable Ventures also receives a rebate from Xcel and a significant federal tax deduction. The project has also yielded reduced electricity costs for DIA.

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APPENDIX E: BEST PRACTICES SUMMARY

Caltrans Project No. P1253
Caltrans Task No.

Solar Power Initiative Using Caltrans Right-of-Way— Best Practices Summary

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LIST OF ACRONYMS

A	Ampere
AC	Alternating current
AHJ	Authority having jurisdiction
AM	Air mass
ASTM	American Society for Testing Materials
BOS	Balance of system
CAISO	California Independent System Operator
Caltrans	California Department of Transportation
CdTe	Cadmium telluride
CEC	California Energy Commission
CIGS	Copper indium gallium selenide
cm	Centimeter
cm^2	Centimeter squared
c-Si	Crystalline silicon
CPUC	California Public Utilities Commission
DC	Direct circuit
DOT	Department of transportation
EPS	Electric power system
GW	Gigawatt
Hz	Hertz
IBC	Interdigitated back contact
IEC	International Electrotechnical Commission
IEC TC	International Electrotechnical Commission Technical Committee
IECRE	IEC Renewable Energy

IEEE	Institute of Electrical and Electronics Engineers
I_{SC}	Short-circuit current of solar module (in this case, as labeled on nameplate)
ISE	Interconnection system equipment
ISO	International Organization for Standardization
ITS	Intelligent transportation system
kWh	Kilowatt hour
LED	Light-emitting diode
m/s	Meters per second
m^2	Meters squared
MLPE	Module-level power electronics
MW	Megawatt
NEC	National Electrical Code
NEM2A	Net Energy Metering Aggregation, Phase 2
NFPA	National Fire Protection Association
nm	Nanometer
NMOT	Nominal module operating temperature
NOCT	Nominal Operating Cell Temperature
NREL	National Renewable Energy Laboratory
O&M	Operations and maintenance
PID	Potential-induced degradation
P_{max}	Power generated by solar module (in this case, as labeled on nameplate)
PPA	Power purchase agreement
PV	Photovoltaic
PVUSA	Photovoltaics for utility-scale applications
RECB	Renewable Energy Certification Body

RSP	Reference System Portfolio
SCE	Southern California Edison
SEMI	Semiconductor Equipment and Materials International
STC	Standard test conditions
TOU	Time of use
TWh	Terawatt hour
UL	Underwriters Laboratory
UV	Ultraviolet
V	Voltage
V_{OC}	Open-circuit voltage of solar module (in this case, as labeled on nameplate)
W	Watt
W/m^2	Watts per meters squared
Wdc	Power rating in watts of solar modules

GLOSSARY

Note: Some of the terms listed here take on a slightly specialized meaning in the context of solar systems. This glossary is intended to help clarify important solar-related terms for readers of this document.

Air Mass: The mass of air through which solar beam radiation passes relative to the mass it would pass through if the sun were at the peak (zenith, i.e., directly overhead) at sea level. For a location at sea level, air mass is 1/cos(!), where **!** is the zenith angle.

Ancillary Services: Services commonly supplied by batteries or other grid components to maintain grid stability and security. These include frequency control, spinning reserve, and operational reserve.

Angle of Incidence: The angle by which the solar radiation strikes a surface.

Angular Dispersion: The range of angles found in a beam of light.

Array Cleaning: The action of making an array clean, which may be done with or without water.

Authority Having Jurisdiction: A local authority with legal mandate to determine whether local codes and standards are accurately implemented.

Backtracking: A tracker-control algorithm that points the modules at the sun through most of the day until near sunset. Then, as the adjacent rows begin to shade each other, it moves the trackers back toward a horizontal configuration to avoid row-to-row shading. Backtracking is useful for silicon systems, but not usually for thin-film (e.g., cadmium telluride [CdTe]) systems.

Balance of System: The components required to assemble a photovoltaic system, with the exclusion of the photovoltaic modules. These may include power electronics, mounting systems, wiring, fuses, switches, and combiner boxes. Modern systems may also include batteries and associated power electronics.

Bandgap: The energy difference between the maximum energy state in the valence band and the lowest energy state in the conduction band, defining the smallest photon energy that is absorbed by a material.

Battery Storage: A type of energy storage that stores electrical energy as chemical energy and is able to convert it back to electricity when desired.

Cable Tie: A bendable plastic strip that has an insertable hole on one end that locks inside an opening hole on the other end. Once in place, the action is irreversible, and the tie can only be removed by cutting. While cable ties appear to be a small detail in a system, many systems have been built with cable ties that deteriorated with weathering, triggering the need to replace all cable ties in the system. Identifying a durable source of cable ties is a good practice.

Cadmium Telluride: A binary semiconductor made from cadmium and tellurium and implemented in thin-film solar photovoltaic modules usually using glass construction for both the frontsheet and backsheet. These modules have historically been lower in cost than silicon modules because of the very minimal semiconductor material usage. Cadmium telluride modules comprise a few percent of global solar manufacturing with almost all of that manufacturing completed by a single company, First Solar (the largest U.S. manufacturer).

Cast Mono: A type of crystal-growth method that nucleates growth from monocrystalline silicon wafers. Cast mono provides the excellent performance of monocrystalline silicon technology with the lower price associated with multicrystalline silicon technology.

Central Inverter: Power electronics that convert direct circuit (DC) electricity to alternating circuit (AC) electricity for very large solar systems (1 MW–10 MW). See Table 6.5 and associated discussion.

Clipping: An action that occurs when the output of a solar system is limited by the AC rating of its inverter instead of by the DC output of the solar modules. The solar modules are moved into forward bias, and the extra energy ends up in heat in the modules.

Conductor: A type of material that conducts electrical current through the transmission of electrons.

Copper Indium Gallium Selenide: Thin-film solar modules made from these elements comprise on order of 1 percent of the world photovoltaic market in recent years. They are viewed as being lower cost than silicon modules, but they have not been able to capture more than about 3 percent of the world market share. The majority of deployment has been dominated by a single company, with other companies developing consumer products for niche markets.

DC-DC Power Optimizers: Power electronics that adjust the relative voltage and current coming from a solar module to match the currents of other modules in a string. These optimizers reduce and stabilize the impact of module shading of the system and allow each module to operate at an optimal bias even when that bias differs for each module in the string. These optimizers have gained market share in recent years. See Table 6.5 and associated discussion.

Diffuse Radiation: Radiation dispersed by the atmosphere due to particles in the atmosphere.

Dual-Axis Tracking: When solar modules are mounted on a surface that is then moved by tilting, as needed, to point at the sun through the day and year.

Electrolyzer: A device that splits water into hydrogen and oxygen through the use of electricity.

Emissive Power or Radiant Self-Exitance: The rate at which solar radiation energy over a surface per unit area exits by emission only.

Encapsulant: A thin, low-cost, low thermal resistance, protective, transparent material that covers a solar photovoltaic cell structure to retain a fully composed solar module.

Ethyl Vinyl Acetate: A polymer that has been the most commonly used encapsulant material for solar modules.

Frequency Support: An ancillary service provided to keep the frequency of the grid AC power stable. When the demand for electricity increases beyond the grid's current ability to deliver electricity, additional energy is injected into the grid to restore the balance and maintain a stable frequency.

Generator: A device that converts energy into electricity. It typically refers to the conversion of mechanical energy to electrical energy.

Global Dimming and Brightening: The decrease of terrestrial solar radiation from the 1950s to the 1980s in the worldwide observational networks ("global dimming") and a more recent recovery ("brightening"). The effect is thought to be dependent on air pollution.

Ground-Mounted Systems: Solar systems that are mounted on the ground rather than on a building.

Ingot: A cooled, solid, pure material formed during manufacturing. In this context, the ingot is formed when the polysilicon feedstock is converted into the higher-purity and crystal structure silicon that is ready to be made into wafers and then solar cells.

Insolation: The solar energy incident on a surface over a period of time. Insolation is commonly represented by *H*. It represents the irradiation in the solar energy spectrum. Its units are kilowatt hour per meter squared (kWh/m^2).

Installer: A company that designs and installs systems. Some installation companies also provide operations and maintenance services.

Inverter: A device that converts DC electricity from solar modules or batteries to AC electricity.

Irradiance: The solar radiation incident per unit area over a surface. It is usually reported as watt per square meter (W/m^2). It is represented generally by the letter *G* followed with appropriate subscripts for beam, diffuse, or spectral radiation.

Load Profile: The electricity load as a function of time. It is usually considered in the context of evaluating the need for supplying electricity as a function of time to match the load profile.

Maximum-Power-Point Tracking: An adjustment of the operating voltage of a solar module or string of solar modules at the voltage that maximizes the product of the current and voltage generated by the module or string of modules. In today's systems, this is usually done by an inverter. Systems with DC optimizers do the maximum-power-point tracking at the optimizer and use a simplified inverter that does not need to do the maximum-power-point tracking.

Microinverters: Small inverters installed in the back of each solar module where it can convert DC electricity to AC electricity to effectively make an "AC module." See Table 6.5 and associated discussion.

Module-Level Power Electronics: Power electronics at the module level that include microinverters and optimizers. See Table 6.5 and associated discussion.

Module: A package of interconnected solar cells. The solar cells are wired in series and sometimes in parallel and encapsulated between a frontsheet and a backsheet to provide protection from the weather. Modules are connected together to form a PV array.

Monocrystalline: The single-crystal form of a material. Solar modules made from monocrystalline silicon typically provide a slightly higher efficiency and are slightly more expensive than those made from multicrystalline silicon.

Multicrystalline: The polycrystalline form of a material usually fabricated by casting. Solar modules made from multicrystalline silicon typically provide a slightly lower efficiency compared with those made from monocrystalline silicon and are slightly less expensive. Historically, multicrystalline silicon modules have captured the largest fraction of market share, but that balance has recently shifted toward monocrystalline silicon, though cast-mono silicon may become the new industry leader in years to come.

Nominal Operating Cell Temperature (NOCT): The operating temperature of a solar cell in a solar module when operating under the following test conditions: irradiance = 800 W/m^2, air temperature = 20°C, wind velocity = 1 m/s, mounting = open rack, and bias = open circuit. This temperature is typically about 40–45°C and may be used to estimate the operating temperature under a range of conditions. Nominal module operating temperature (NMOT) is the module temperature when the module is biased at the maximum power point under similar operating conditions. IEC has recently changed from measuring NOCT to measuring NMOT as a better representation of module temperature.

Non-synchronous Generator: Solar modules are considered to be non-synchronous generators because they generate electricity without having a mechanical inertia that helps to maintain the frequency and phase of the AC electricity.

One-Axis Tracking: A type of tracking that rotates around one axis to enable solar modules to collect more sunshine. The most common implementation uses a north-south axis that rotates to the east in the morning and to the west in the afternoon, with many rows of modules controlled by a single controller to keep the costs low. Tracking is used on many utility-scale systems today but is uncommon on rooftop solar systems.

Open-Circuit Voltage: The electrical potential found between the positive and negative terminals of a solar module when no current is flowing.

Optimizer: See DC-DC Power Optimizers above.

Peak Sun Hour: The hour when the solar irradiance (intensity of sunlight) reaches a maximum, typically about 1000 W/m^2.

Perovskite: A relatively new class of solar cells using various compositions with a structure similar to that of calcium titanium oxide. The progress with this new class of solar cells has been impressive, generating much excitement, though industry veterans are skeptical that it will succeed in surpassing existing thin-film technologies such as CdTe. Current development is focused on addressing stability, reliability, and scalability.

Photo Current: The electrical current generated when light strikes a solar cell.

Photons: Particles that transmit light through the form of an electromagnetic wave as energy packets.

Photovoltaic Effect: A process by which a solar cell generates electricity when exposed to sunlight.

Polysilicon: The silicon feedstock used for making silicon solar cells after ingot and wafer formation.

Potential-Induced Degradation: Degradation of solar modules caused by the voltage generated by the modules themselves. This effect typically is accelerated by moist conditions and is caused when current flows through the glass material protecting the cells. It is believed to be caused by sodium moving out of the glass and into the solar cells and can be prevented by a change in the design of the solar cell, solar module, or solar system design.

Power Factor: The ratio of the electrical power delivered to the electrical power that would have been delivered if the AC voltage and AC current had been perfectly in phase.

Pyranometer: An actinometer used for measuring solar irradiance (beam, diffuse, or spectral) on a planar surface. It measures the solar irradiance (W/m^2), quantifying the heat produced by the incident light. It does not have the same spectral response as a solar cell.

Pyrheliometer: A device for measuring direct-beam solar irradiance, quantifying the heat produced by the incident light. It does not have the same spectral response as a solar cell.

Reactive Load: An electrical load that does not draw voltage and current in a completely synchronous (in-phase) fashion.

Roof-Mounted Systems: Solar installations that are directly mounted onto the roof of a building.

Solar Beam Radiation: Direct solar radiation obtained from the sun without being scattered by the atmosphere.

Solar Resource: The solar insolation received at a location as a metric to assess the value of installing a solar system at that location.

Solar Time: The time based on the apparent angular motion of the sun across the sky, which is usually different from the local clock time.

Spinning Reserve: Generators that are moving synchronously with the grid and are effectively in standby mode to begin generating electricity at a moment's notice if needed.

String Inverters: Inverters that are connected to a string of solar modules. See Table 6.5 and the associated discussion.

Synchronous Generator: A generator that generates AC electricity at the same frequency and phase as the grid electricity, helping to keep the frequency and phase stable.

System AC Power Rating: The output power rating of the inverter of a solar system (or sum of these ratings when there are multiple inverters).

System DC Power Rating: The sum of power ratings of the solar modules in a solar system.

Time-of-Use Rate: The variable rate for the cost of electricity, typically changing with time, season, or day to reflect the availability of electricity. See Figure 2.4 for an example.

Total Solar Radiation (Global Radiation): The total sum of the solar beam radiation and diffuse radiation incident on a surface.

Tracker: A device that moves solar modules to better face the sun at all times during the day.

UV Radiation: Electromagnetic radiation waves emitted by the sun that have wavelengths from 10 nm to 400 nm.

Zenith Angle: The angle between the zenith (position vertically overhead) and the sun.

1 Introduction and Scope

1.1 Why Solar in the Right-of-Way

1.1.1 Why Solar

The State of California has set the goal (Senate Bill 100 [SB 100]) of reaching 100 percent zero-carbon energy by 2045. California's primary strategy for reaching zero-carbon energy has been to increase generation and use of solar electricity. According to the Energy Information Administration, solar electricity generation in California has more than doubled in the last four years, from 20.8 terawatt hours (TWh) in 2015 to 43.8 TWh in 2019, approaching 20 percent of the electricity generated in California. In recent years, the cost of solar electricity has dropped impressively, allowing it to compete directly with conventional electricity at both the wholesale and retail levels. California is blessed with abundant solar resource, especially during the times of year when electricity demand is highest. The combination of low prices and relatively consistent availability make solar an attractive option for providing a substantial fraction of the 100 percent zero-carbon electricity targeted by SB 100.

Other renewable energy sources will have to contribute to the 100 percent zero-carbon energy goal as well. For example, wind electricity has increased from 12.2 TWh in 2015 to 15.0 TWh in 2019. Wind is also a very attractive resource for California in reaching the goals of SB 100; however, wind plants may cause visual distraction to motorists and may bring environmental issues such as noise and unacceptable height. Also, California is blessed with an abundance of excellent solar sites, and a smaller number of excellent wind sites. Thus, this study focused solely on solar installations.

1.1.2 Why Solar in the Caltrans Right-of-Way

The California Department of Transportation (Caltrans) has recognized its right-of-way as a resource to the state of California. In particular, the unused space at diamond and cloverleaf intersections provides airspace that could be used for solar installations. Such spaces can often allow access from a street and provide adequate space for locating the solar system outside of the clear recovery zone. Two previous attempts to utilize such airspace for solar projects were abandoned before the projects were completed. This study was designed to lay the foundation for future solar deployments.

In general, the most attractive right-of-way sites are locations with ample space available, especially to accommodate future widening of a highway, and where there is a planned electrical load.

1.2 Why NOT Solar in the Right-of-Way

Solar systems have achieved very low prices, largely because of economies of scale. A key element of achieving these low costs has been the ability to develop modular designs that can be applied repeatedly. For example, 2-megawatt (MW), 10-MW, or even 100-MW systems may be built using a 1-MW modular design, reducing the cost of project-specific engineering. Rooftop solar has also developed fairly modular designs for the hardware and automated techniques using satellite images to tailor these modular designs to specific projects without the need for an engineer to visit the home and climb on the roof. Solar installations on new construction benefit from the possibility of a single design being duplicated on every house in a housing development.

It is less clear if deployment of solar systems in the right-of-way will provide a similar opportunity for minimizing project-specific design costs and/or reducing costs associated with deployment scale-up. Thus, if the goal is to supply low-cost solar electricity, it might be preferable to participate in a large solar installation that is optimally sited rather than attempt to install a solar system that is close to the load but in an awkward location.

Locations available in the right-of-way may not be well suited for solar installations because of their available geometric space, terrain, lack of grid accessibility, or other challenges. Tracts of land available alongside a highway are long and skinny, usually requiring the electricity to be transmitted some distance to the point of grid interconnection, thus adding to the cost of the system. A common challenge is that in urban areas, where grid access is nearby, the right-of-way is typically limited to the minimum width allowable based on clear-zone safety requirements, while in rural areas, where grid access might not be available, right-of-way is less limited. In addition, any location that may be subject to widening of a highway within the desired lifetime of a solar system (25–30 years) is a poor candidate.

Compared to the area adjacent to the roadway, the parcels of land available in diamond and cloverleaf interchanges may accommodate more rows of modules, reducing the distance that the electricity needs to be carried. These parcels are often of odd shape or on sloped terrain, requiring higher project-specific engineering costs. Some locations are without easy connection to the grid or may at least require trenching on the highway shoulder or lateral drilling to install the needed electrical connection to the grid.

1.3 Scope of this Document

1.3.1 Other Reports from this Project

This report, *Best Practices Summary*, complements the other reports prepared as part of Project P1253. In general, information in those documents is not repeated here but may be derived directly from those reports:

- *Literature Review Summary*—Summarizes literature available about projects undertaken by the departments of transportation (DOTs) in other states.
- *Summary of Rules and Regulations*—Summarizes federal, California, and other state rules and regulations related to deployment of solar systems in the right-of-way.
- *Follow-Up Interview Summary*—Summarizes interviews with DOTs in other states on what they found successful and what issues they encountered.
- *Financial Opportunities Assessment*—Summarizes financial mechanisms that may be considered for public-private partnerships or other options for financing solar systems.

- *Final Research Report*—Summarizes the entire project, including what went well with the project and what issues were encountered, as well as some projection about future expectations for the solar industry.

These reports are available on the internal Caltrans project website, https://solar.onramp.dot.ca.gov, or upon request from the Caltrans Division of Research, Innovation, and System Information.

1.3.2 Facilitating Management of Solar Projects

This best practices summary is designed to facilitate efforts by Caltrans to utilize the right-of-way for solar projects. It is intended to be used by Caltrans engineers who are already experienced with construction projects but have little experience with solar energy and solar photovoltaic (PV) systems. This document reviews the parts of a solar system, how the design of the system can best take advantage of the available solar resource, how to select a site for a solar deployment, how to ensure success at each stage of construction of solar systems, and how to maintain the solar systems over their decades of operation. Two case studies are analyzed to facilitate understanding of the material.

This summary is based on research conducted by UC Merced and the Texas A&M Transportation Institute, in particular a literature review; a review of applicable federal, state, and local laws, rules, and regulations; and a series of interviews conducted with state DOT officials who had experience with large-scale solar project implementations in their state. This document also assumes that Caltrans will work directly with solar installation contractors[1] who will be familiar with local code requirements and who have already demonstrated successful deployment of solar systems.

1.3.3 Managing Rather Than Executing Solar Projects

The focus of this document is on knowledgably managing solar project execution. The document does not focus on how to design and install solar systems. While Caltrans may be large enough to eventually develop an internal capability to execute solar projects, there are two reasons why it is a best practice for an organization like Caltrans to contract with a solar installation contractor: (a) economics, and (b) the learning curve.

1.3.3.1 Economics of Mass Production

The dramatic reduction in solar prices is largely a result of economies of scale: solar installation contractors have been able to streamline the installation process by gaining experience with a specific set of hardware (and consistent system design), reducing the time and effort needed for designing a system, decreasing the number of parts that need to be stocked, and facilitating rapid installation. As an example, companies installing a utility-scale system have designed a block that installs 1 MW. Whether a customer wants a 1-MW plant, a 100-MW plant, or

[1] The term "installation contractor" is used to refer to a company that designs solar systems, procures the parts for those systems, and installs the systems. Such a company may write a contract with Caltrans to deliver a system that is owned by Caltrans or may write a contract to lease airspace for a system that the company will own. If a company designs and installs systems but does not write a contract with Caltrans, the company will be referred to as a developer, but the skills are similar. Both are commonly referred to as "installers."

something in between, the design in every case is built from 1-MW blocks, resulting in very minimal design cost for each new system.

1.3.3.2 Climbing the Learning Curve

The interviews with other DOTs, for example, the interview with the Florida Department of Transportation, led to a clear conclusion: putting together a solar system is a straightforward project that can be done by most any engineer, but putting together a solar system that will not have future issues is not straightforward. The reasons for failures can be wide ranging, including (as examples to show the wide variety of problems that have been observed, not as an exhaustive list):

- Selecting an inappropriate module type that leads to a high failure rate in the fielded application.
- Using a combination of metals that corrode (as was the case in Florida).
- Installing cables that blow in the breeze or expand and contract in a conduit and become abraded, sometimes leading to ground-fault interrupts and possibly a fire.
- Installing an unsuitable surge protector.
- Failing to install a surge protector.
- Replacing the module clamp with a different clamp because the first one is not available, resulting in excessive module breakage.
- Finding that the local ant population loves the taste of a material in the junction box.

Some design errors are caught quickly, while others may take years to become apparent and be resolved. Thus, working with an installation contractor who has already climbed the learning curve locally in California can circumvent severe headaches later on.

This best practices summary includes solar-specific information for managing construction projects, but not for the design and construction itself since the construction should be completed by a company that specializes in solar system construction.

2 UNDERSTANDING THE SOLAR RESOURCE

2.1 Understanding the Importance of Solar Resource for Successful Business Outcomes, Including the Role of Storage

Definitions of terms related to solar resource are included in the glossary at the beginning of this summary. A standardized complete description of terminology and all measurements related to solar systems can be found in International Electrotechnical Commission (IEC) 61724-1, *Photovoltaic System Performance – Part 1: Monitoring.*

2.1.1 Terminology and Solar Resource Basics

The solar resource is measured by the solar *irradiance*, which quantifies the amount of sunlight striking a surface at a specific time, and by solar *insolation*, which quantifies the amount of sunlight striking a surface integrated over time. Solar irradiance is measured in watt per meter squared (W/m^2), and solar insolation is measured in kilowatt hour per meter squared (kWh/m^2) for a specific period of time—often per day or per year.

Power is the rate at which energy is being used, transferred, or converted (for example, a 60-watt (W) light bulb uses 60 W of power), while energy is the power integrated over a period of time (for example, a 60-W light bulb that is used for 10 hours uses 600 Wh of energy, or 0.6 kWh). Solar irradiance is to solar insolation as power is to energy.

Solar irradiance is often divided into two parts: the direct beam and the diffuse light. The direct beam comes straight from the sun and has only a very small angular dispersion associated with the size of the disk of the sun. Diffuse light has been scattered as it makes its way through the atmosphere. Shading results from the direct sunlight being blocked. The diffuse light will still illuminate the area that is shaded. In general, blue light (shorter wavelength light) is scattered more than red light (longer wavelength light), which is why the sky appears blue and the rising and setting sun appear red. The global irradiance is the sum of the direct and diffuse irradiance.

2.1.2 Measurement of Solar Resource and Weather Parameters

Solar irradiance is often measured using a pyranometer (Figure 2.1). Although the term pyranometer may be used for multiple types of devices, it usually refers to a thermopile that measures the heat associated with the hemispherical light striking a surface. A thermopile is a set of many thermocouples (junctions of dissimilar metals) and measures the difference in temperature between the front and the back of a black surface sitting in the sun. It typically has a dome-shaped glass over it to facilitate light striking the surface from any direction. The signal measured from a thermopile is voltage (V); typically, the measured voltage is < 1 V, but the exact voltage depends on the design of the thermopile.

Figure 2.1. Example of pyranometer. The glass dome allows light to strike the black thermopile from any angle.

Many solar systems use a PV reference cell for measuring the irradiance (Figure 2.2). A reference cell operates essentially in the same way as the solar modules in the solar system: nominally each photon that is absorbed by the solar cell generates an electron that can be used in an external circuit. While a thermopile is recording a voltage, the important parameter to measure from a reference cell is the electrical current. However, the reference cell is often equipped with a resistor so that the current is converted to a voltage before measurement. It is important that the resistor be small (often on order of 1 Ω) so that the output voltage never approaches the open-circuit voltage of the solar cell, which would cause the reference cell's measured response to become nonlinear with irradiance. Alternatively, an operational amplifier may be used to measure the current.

Figure 2.2. Silicon reference cell.

Both thermopiles and reference cells need to be calibrated for the measurements to be accurate. They are usually calibrated to give a signal that corresponds to an incident irradiance of 1 kW/m^2, which is typically considered to be "one sun" since 1 kW/m^2 is a common irradiance for a surface in direct sunlight on a clear day. The irradiance measured by side-by-side pyranometers and reference cells will track very closely, but the measurements commonly vary. There are two primary differences between them. First, the pyranometer is measuring heat (a temperature difference reflecting the power in the sunlight), while the reference cell is measuring the photocurrent (the number of photons absorbed and collected by the solar cell). When the spectrum of the sunlight changes significantly, the difference between the measured irradiance of the two can be a few percent. The second difference between the two types of sensors is their response to light striking them at different angles. The response of the pyranometer has been engineered to capture light striking from the full hemisphere above it (any light coming from the front side). The reference cell also can respond to any light striking from the front, but glass tends to reflect more light that strikes at a higher angle of incidence, so the reference cell usually misses responding to a larger fraction of the diffuse light. On a clear day, this difference is typically 1–2 percent, but the relative difference may be greater on a cloudy day.

It is common practice to install either a thermopile, a reference cell, or both next to a large solar system so that the output of the solar system can be compared to the measured irradiance. Highly accurate thermopiles typically cost thousands of dollars. An accurate reference cell typically costs < $1,000. Inexpensive reference cells can be purchased, but they may be less accurate, and they may degrade. Some installations use a reference solar module in place of the reference cell. The reference module will be a closer match to the performance of the solar system and may cost about the same as the reference cell since the modules are made in large volume.

A pyrheliometer is another type of instrument used to measure the irradiance of the direct beam of solar radiation. Like pyranometers, pyrheliometers are used to quantify the solar resource as a reference for the measured output of the solar system. A pyrheliometer needs to be mounted on a two-axis tracker so that it is always aimed at the sun. Because of the need for the tracker and for maintenance to keep the tracker pointed at the sun, pyrheliometers are often omitted from the meteorological stations for solar systems. A lower-cost, though also lower-accuracy, approach to measuring the irradiance in the direct beam is use of a shadow-band radiometer. The shadow-band radiometer measures the output as a band is passed over the sensor and then takes the difference between the signal in the full sun and the signal in the shade to calculate the irradiance in the direct beam. If the direct-beam irradiance and the diffuse irradiance are both measured, they are used to estimate the irradiance on any surface no matter its orientation using any of a number of transposition algorithms. This can be especially useful if modules are mounted in different orientations in the same system, as would be expected for a roof-mounted system on a roof that faces partly south but also partly east or west.

The solar irradiance may also be quantified from satellite data. Explaining the principles of how solar irradiance data are derived from satellite data is outside the scope of this summary, but Section 3.3.2 contains further discussion on satellite-derived irradiance data.

The solar insolation varies with location and with the orientation of the mounting surface in question. In the United States, the daily insolation on a horizontal surface is greater in the summer, while the insolation on a south-facing surface will be higher in winter. The insolation as a function of location and mounting configuration can be found from many sources. An example of one source that helps illustrate the effect of the mounting of solar modules is a database that can be found at https://nsrdb.nrel.gov/data-sets/archives.html. To reach the file, Download the 1961-1990 Archive Data, then open the "statistics" folder and a folder called "redbook." This database summarizes data collected over 30 years. Moreover, Section 3.2 describes a simple tool for looking up the insolation for any location in the United States.

In addition to measuring the solar irradiance, measuring the temperature, wind speed, and other meteorological details can be useful. Ambient temperature measurements are typically measured using a sensor that is shielded from direct sunshine, as shown in Figure 2.3. There are many types of sensors for wind speed. An anemometer is shown along with a weathervane for measuring wind direction in Figure 2.3. It is conventional to measure wind speed 10 m above the ground. Similarly, the ambient temperature sensor should be positioned away from heat sources but in a representative location.

Figure 2.3. Sensors for measuring meteorological conditions.

2.1.3 Importance of Annual Solar Resource to Project Success

Projects that value all electricity equally may estimate the value of the project from the annual insolation. An example of this is a power purchase agreement (PPA) made with a customer who has need for the electricity. Historically, 25-year PPAs were common, but today, fewer customers are willing to sign a 25-year PPA and may limit the PPA to 10 years.

Caltrans may use the electricity directly, avoiding the need for a PPA. In this case, the value of the project is reflected in the reduced electricity bill. Electricity bills may be calculated in many ways. In general, net metering requirements allow the owner of a system to return electricity to the grid during times of surplus generation and then draw electricity from the grid at night, with the bill reflecting the net electricity used. Typically, the balance between electricity generation and usage shifts between summer (longer days) and winter (shorter days). Thus, net metering arrangements generally allow credit for excess generation to be carried through the year, making the annual electricity generation relevant to the success of a project.

2.1.4 Importance of Daily and Seasonal Solar Resource for Successful Business Outcome

Although net metering in California dictates that the electric bill reflect the net electricity used, all solar customers are required to sign up for time-of-use (TOU) rates, which may place less value on electricity generated when the sun is shining. Currently, the difference in the price of electricity during the day and at night is small in many locations, but TOU rates have been changing to reflect the surplus of electricity that is seen during the day in California because of the many solar systems. An example is shown in Figure 2.4. These data indicate that a kWh generated in December (between 8 a.m. and 4 p.m.) will be valued at 24 cents. If Caltrans needs to use a kWh of electricity sometime between 4 p.m. and 9 p.m., the charge for that kWh will be 35 cents. The TOU rates reflected in Figure 2.4 are taken from Southern California Edison's (SCE's) webpage. SCE leads California in the adoption of progressive (later in the day) TOU rates (i.e., rates that are designed to motivate behavior that helps the utility to balance supply and demand). These rates can be expected to continue to shift to devalue solar electricity as more solar plants are installed. In Hawaii, with high solar electricity generation but little ability to import and export electricity (which is how California currently balances its grid), the ratio of the rates may be as high as 4, suggesting that 4 kWh of solar electricity must be injected into the grid for every 1 kWh removed during the night.

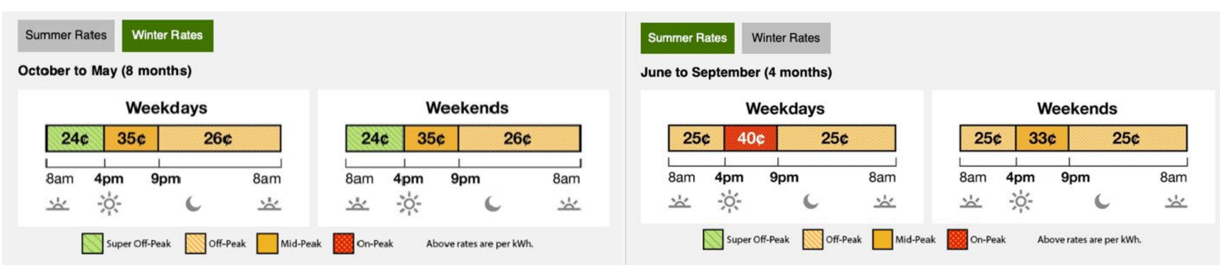


Figure 2.4. Example of TOU rates. Figure source: https://www.sce.com/residential/rates/Time-Of-Use-Residential-Rate-Plans.Figure.

Thus, the value of a given project must consider the balance between the shape of the load profile and the shape of the solar resource. Examples of electricity loads that match well with the solar generation profile are air conditioning loads (especially when the air conditioning can be reduced after sunset) and daytime charging of electric vehicles (e.g., for commuters parking at a park-n-ride). An example of an electric load that has very poor match to solar generation is heating with a heat pump since the heating is needed most during the winter, when the days are short, and at night, when the sun is not shining. Similarly, nighttime lighting requires electricity at exactly the times of day when the sun is not shining. Operation of traffic lights may give much more constant loads throughout the day and night.

If the match between the local load and the solar generation profile is poor, then the excess electricity will need to be transmitted to a location where the electricity can be used. While transmission to a nearby load is usually less expensive than investment in storage, as California increases its use of solar electricity, the nearby loads are likely to already have adequate supply of electricity, potentially requiring the electricity to be transmitted a long distance. In this case, storage is really the only option.

2.1.5 Role of Storage in Shifting Electricity Availability to Match Load

A strategy that is already used today to balance supply and demand is to add a battery. For example, a stand-alone light may use a solar module to charge a battery during the day and then use the stored electricity to power the light at night. It is widely anticipated that future growth of solar deployments in California will need to be coupled with growth of storage in order to balance the supply and demand of electricity.

California has projected the estimated character of the grid to 2045 in a modeled scenario called the Reference System Portfolio (RSP) (California Public Utilities Commission [CPUC] 2019; Sánchez-Pérez & Kurtz 2020a). The RSP projects the supply-demand balance for electricity in California out to 2045, as shown for a fall day in Figure 2.5.

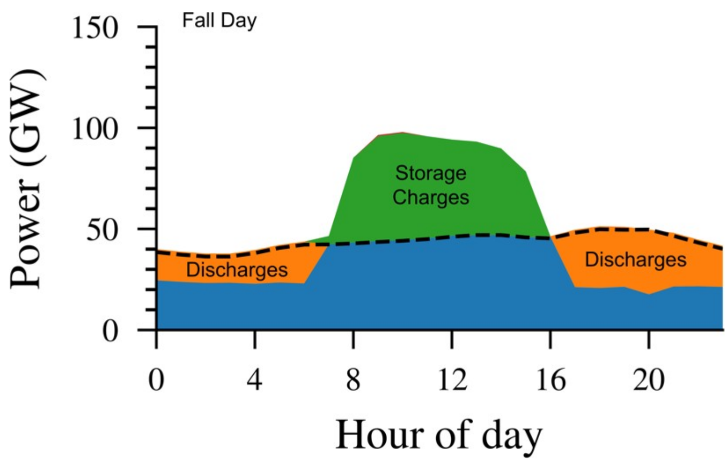


Figure 2.5. Storage charging and discharging from solar electricity. The figure shows a simulation of what the future may hold in 2045 if solar electricity supplies a majority of the electricity needed to drive the grid. During the day when the sun is shining, electricity is used to charge the storage (green area). Then the storage discharges during the night, as indicated by the orange area.

The current projection to 2045 assumes that future installations of solar systems will be coupled with storage systems that can store about half of that electricity to be used at night. Thus, to the extent that the RSP's projections will become reality, it can be anticipated that after some year around 2030, for every solar system that is installed, a storage system will need to be installed with about 10 hours of storage to last through the night. In the near term, many solar systems are being installed with 2–4 hours of storage.

Battery storage is a simple and straightforward way to turn a solar system into a power plant that can dispatch electricity at any hour of the day. However, other forms of storage are often lower in cost and more scalable. For example, a chilled water tank can be cooled with solar electricity during the day and the chilled water used for cooling. As Caltrans assesses the value of a possible project and evaluates the balance between the load that will be served and the solar electricity generation profile, creative efforts to shift the load profile to more closely match the solar generation profile will be very beneficial.

It is also useful to note that as energy storage becomes more critical in the energy transition, many companies are developing technologies that may be superior to batteries. For example, pumped hydropower is currently the most widely deployed storage technology. Pumped hydro may be expanded to new, off-river locations, or modified to use other materials in place of water. Another example of a storage option that may turn out to be particularly relevant to Caltrans is the storage of the excess energy in hydrogen. Multiple companies are developing solar-hydrogen hardware that couples a solar system with an electrolyzer, using solar electricity to split water into hydrogen and oxygen. The hydrogen may then be used later to regenerate the electricity. Of particular interest to Caltrans would be the possibility of selling the hydrogen for use in fuel cell vehicles. Solar-hydrogen stations that could be positioned along major highways would enable refueling of vehicles without the need to transport the fuel long distances, as is typically done today. As the world evolves, new technologies should be evaluated for their potential and their risks.

2.2 California Solar Resource Maps

The solar resource in California is greatest in the southern part of the state and away from the coast, as shown in Figure 2.6 and Figure 2.7. As Figure 2.6 illustrates, California has some of the best solar resource in the country. California exhibits some microclimates, especially along the coast, reducing solar resource near the ocean and elsewhere, as can be seen in more detail in Figure 2.7.

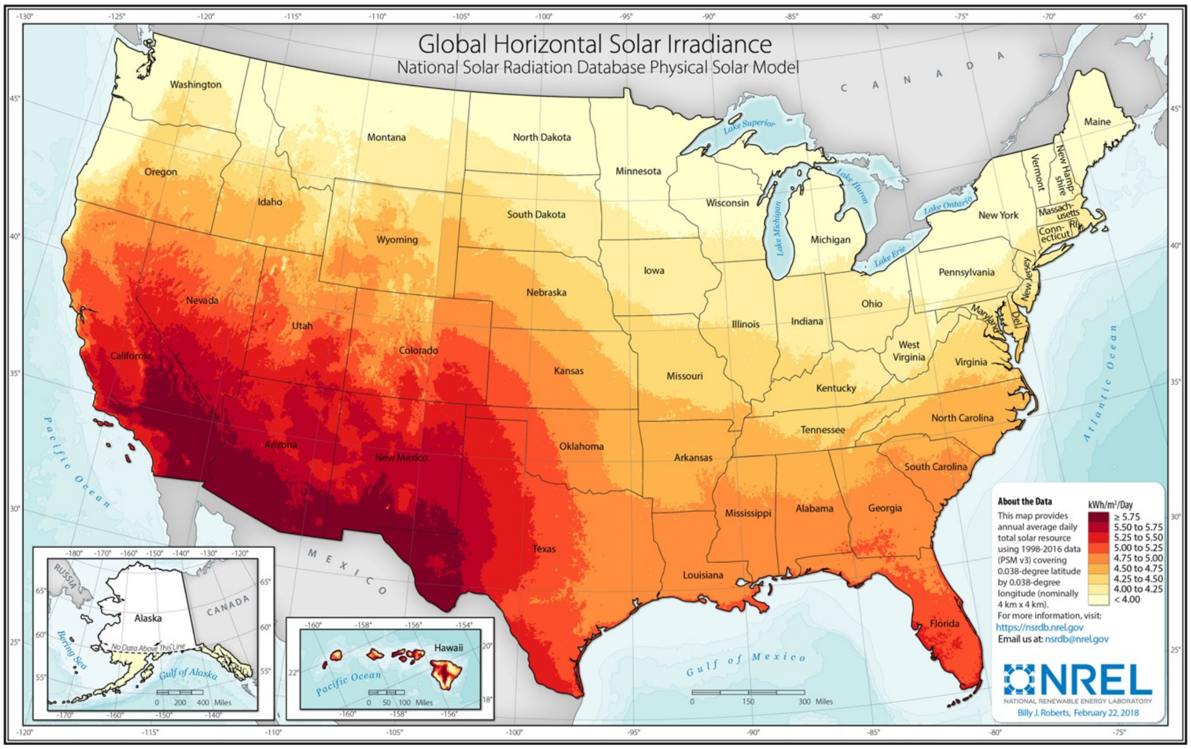


Figure 2.6. Average daily solar insolation in a horizontal plane for the United States. The solar resource for surfaces mounted in other orientations will vary. These data are derived from satellite data from 1998–2016 and can be obtained from https://www.nrel.gov/gis/solar.html on a 4 km × 4 km grid. Image source: https://www.nrel.gov/gis/assets/images/solar-annual-ghi-2018-usa-scale-01.jpg.

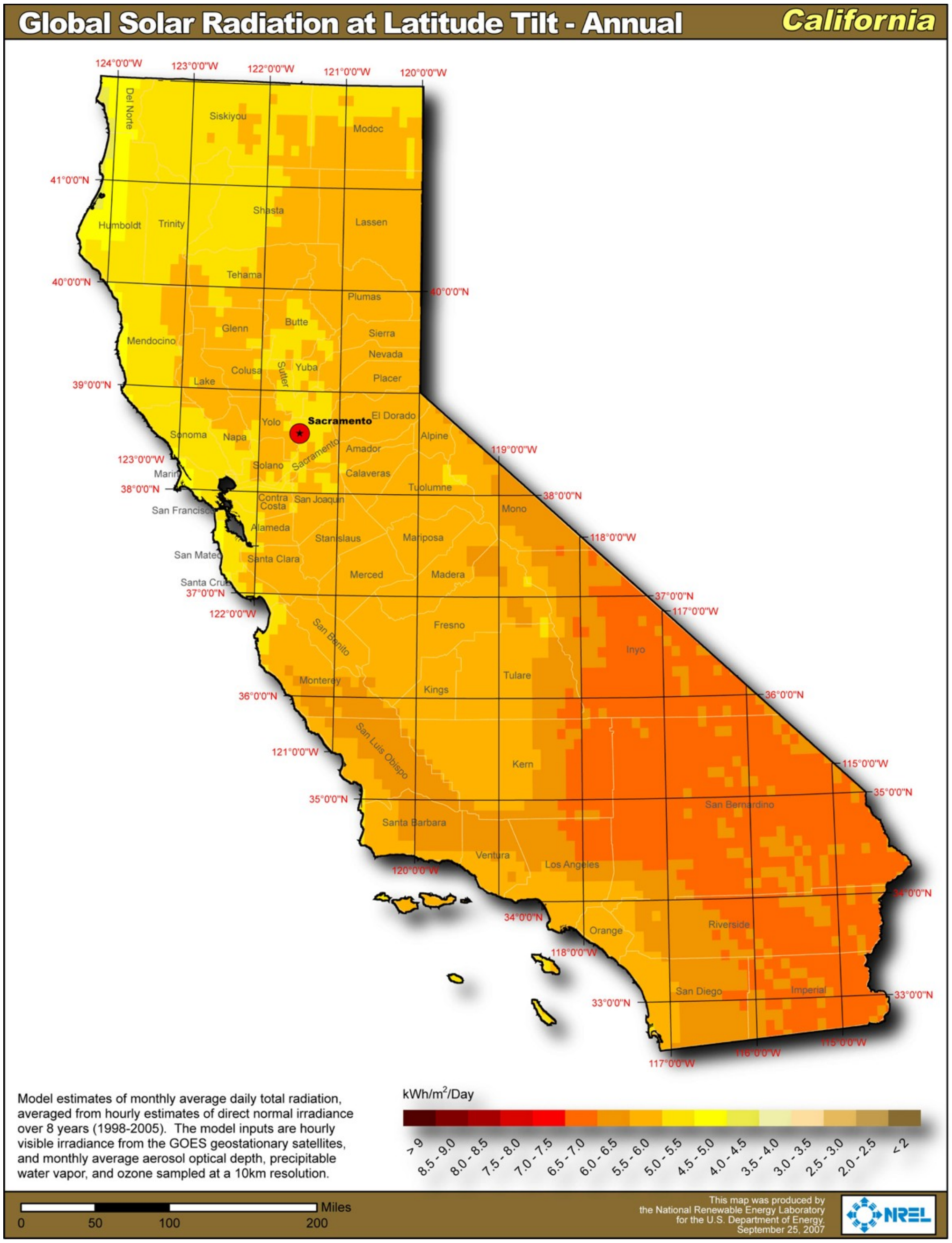


Figure 2.7. Average daily solar insolation in a plane tilted to the south by the local latitude. The solar resource for surfaces mounted in other orientations will vary, as shown in Figure 6.16. These estimates are derived from satellite data from 1998–2005 and are available at https://www.nrel.gov/gis/solar.html on a 4 km × 4 km grid. Image source: https://upload.wikimedia.org/wikipedia/commons/f/ff/NREL-eere-pv-california.jpg.

2.3 PVWatts as a Simple Tool for Evaluating Solar Resource

There are many online calculators for estimating the electricity generation of a solar system. This section introduces the PVWatts® Calculator (National Renewable Energy Laboratory [NREL] 2020b), but other calculators can provide good estimates as well.

In PVWatts, the calculation is initiated by entering the location of the desired system. Next, the PVWatts calculator identifies available solar resource data for that location. Section 3.3 discusses uncertainty in these data sets. If there is more than one data set available for the location of interest, it is a best practice to run the calculation using all available data sets as one indication of the uncertainty in the calculation. Next, the system description is entered, including the size of the array and the mounting configuration. A nice feature of the calculator is to allow the user to draw the dimensions of the system on a satellite map. This provides a quick way to estimate the wattage of a system that will fit in a given location. On the same screen, the local price for electricity can be entered. The final screen of the calculator estimates the kWh generated for a year as well as the monthly generation and the value of the associated electricity. The following pages repeat the above steps with images to guide the reader.

2.3.1 *Data Entry*

The user accesses PVWatts at https://pvwatts.nrel.gov and then begins the calculation by entering an address. An example is shown in Figure 2.8 using the address 3190 Edgewood Rd, Redwood City, CA 94062, which is the location of a Caltrans park-and-ride facility. Latitude and longitude coordinates may also be entered. Once the address is entered in the **Get Started** box, the user presses **GO>>** to get to the next step. The user can select the **HELP** button at any time if questions arise.

Figure 2.8. First screen of the PVWatts tool. Source: https://pvwatts.nrel.gov.

2.3.2 *Solar Resource Selection*

Figure 2.9 shows the second page of PVWatts, which identifies solar resource data sets available for locations near the address that was entered. The database includes a grid of solar resource data derived from satellite data, so PVWatts indicates the nearest grid point for which data are available. For the example address entered, the latitude and longitude are 37.45 and −122.3, respectively, and the distance is 1.2 miles between the grid location and the entered address. Grid points are usually spaced by about 0.04 degrees. If additional data sets are available, they will probably give slightly different results, and may help assess uncertainty in the estimate. If data are available from a ground station, they may be more accurate. The solar resource data are selected to be representative of a typical[2] year rather than being from a specific year. In most cases, only one data set will be identified, and the user may move directly to the next step by clicking the orange arrow on the right above **Go to system info**.

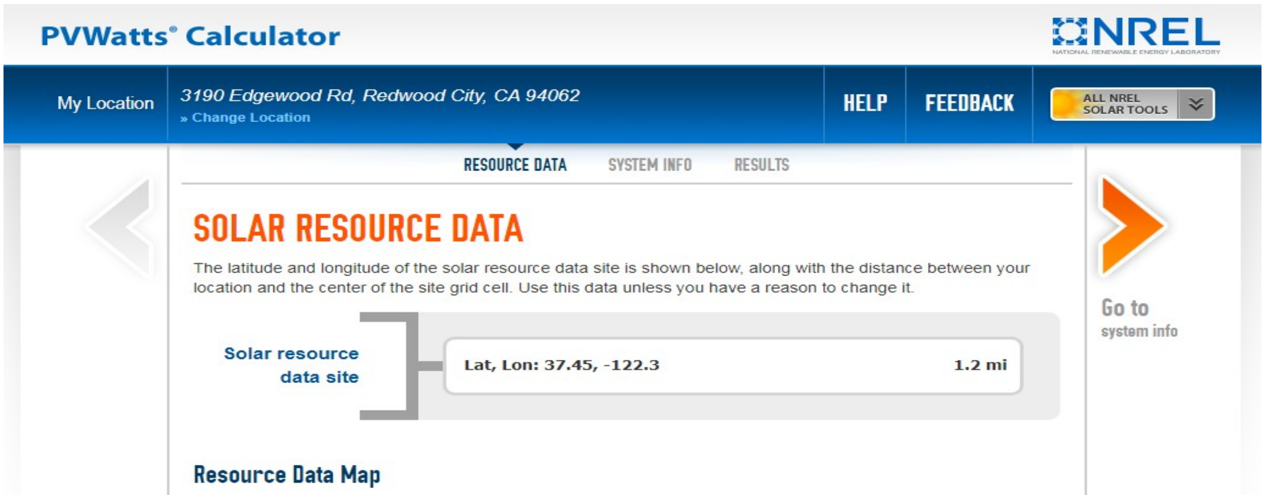


Figure 2.9. Second screen of PVWatts tool—Solar resource data.

2.3.3 *System Design*

Figure 2.10 shows how users can design their own system. If users know the size of the system, they can enter it directly. However, one of the most useful features of this configuration of PVWatts is that users can calculate the direct circuit (DC) system size (kW) by selecting the **Draw Your System** tool shown on the right of the figure. When users first open the tool, they see an animation on how to use the tool (Figure 2.11). Users can close the demo window by clicking **Close X** and then draw their solar system by clicking the corners of the desired positioning of the system—moving either in a clockwise or counterclockwise direction. An example draft is shown in Figure 2.12.

[2] A "typical meteorological year" is assembled from multiple years of data by selecting data month by month. For example, the weather data for the month of January is compared over 30 years, and the January with the median insolation may be chosen. The selection process may also consider temperature and other meteorological parameters. See, for example, https://www.nrel.gov/docs/fy08osti/43156.pdf.

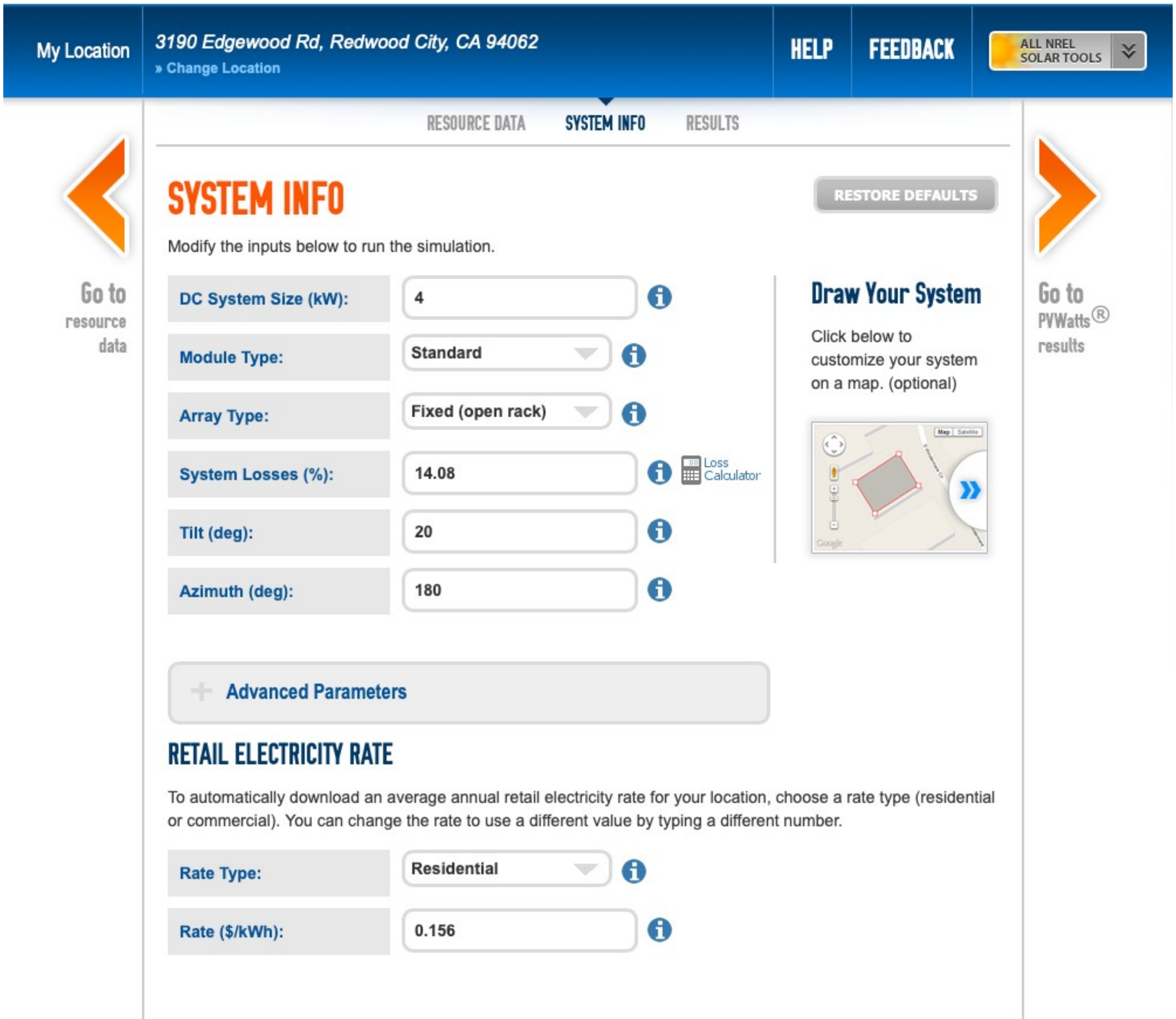


Figure 2.10. Third screen of PVWatts tool—System info.

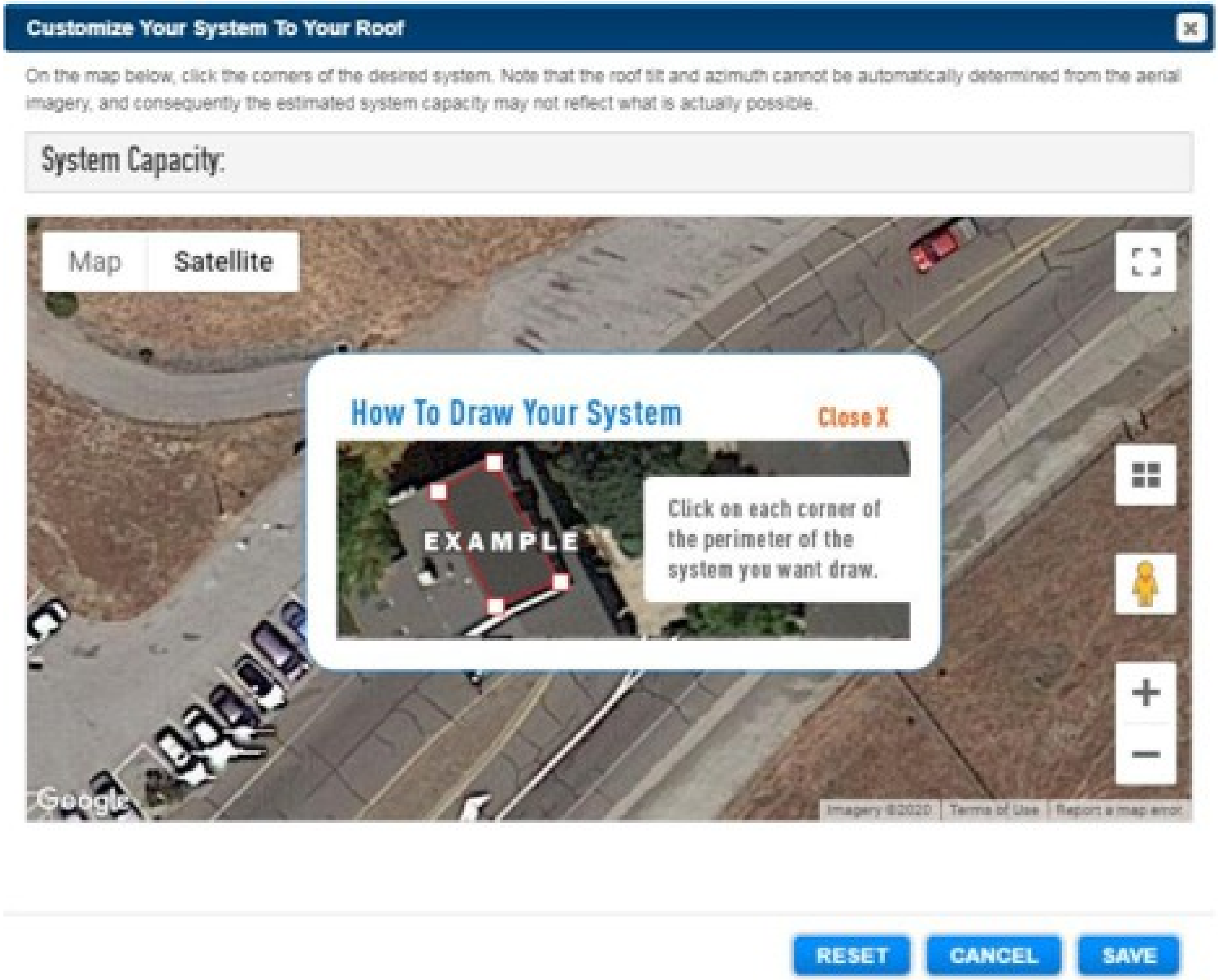
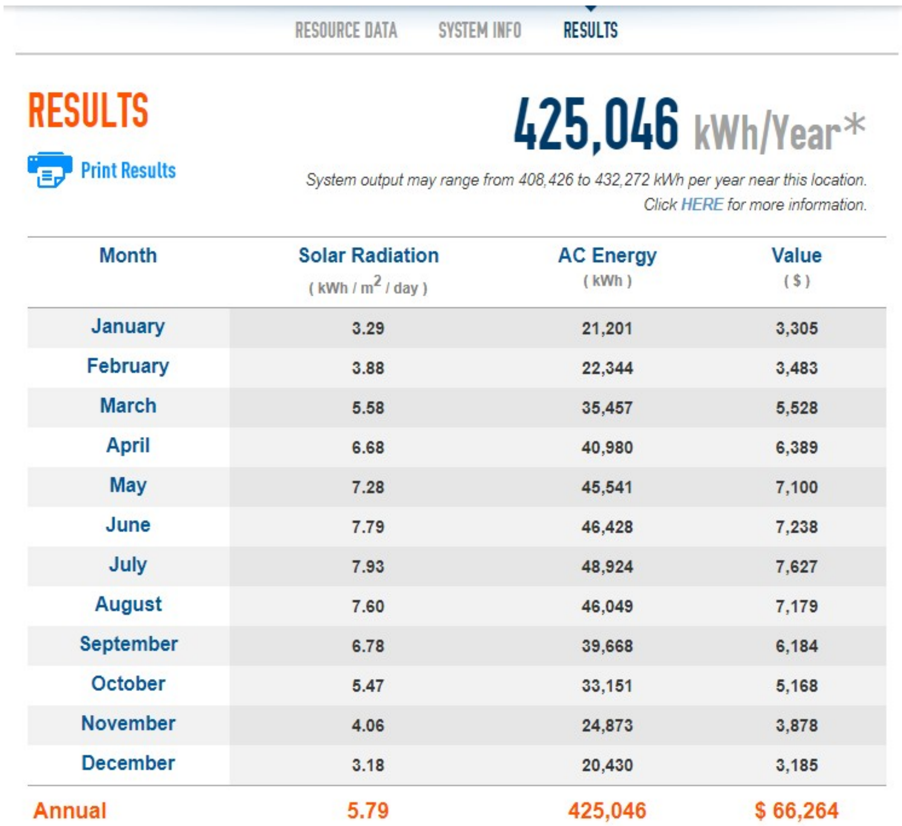


Figure 2.11. PVWatts screen showing how to draw the system. Users must select **Close X** before they can draw a system.

Figure 2.12. Example of how the shape of the desired solar system may be drawn on the map. See red outline.

From the drawn size of the system, the PVWatts tool will calculate the corresponding power rating of the system and enter it automatically. The user can adjust the multiple inputs and advanced parameters to complete the design. Detailed explanations of all these inputs are provided by PVWatts (accessed by clicking on the "i" buttons shown in Figure 2.10), so those explanations are not repeated here. Finally, after the inputs are all defined, the user can click the orange arrow to go to the results page, as shown in Figure 2.13.



RESOURCE DATA SYSTEM INFO RESULTS

RESULTS

Print Results

425,046 kWh/Year*

System output may range from 408,426 to 432,272 kWh per year near this location.
Click HERE for more information.

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	3.29	21,201	3,305
February	3.88	22,344	3,483
March	5.58	35,457	5,528
April	6.68	40,980	6,389
May	7.28	45,541	7,100
June	7.79	46,428	7,238
July	7.93	48,924	7,627
August	7.60	46,049	7,179
September	6.78	39,668	6,184
October	5.47	33,151	5,168
November	4.06	24,873	3,878
December	3.18	20,430	3,185
Annual	5.79	425,046	$ 66,264

Figure 2.13. Final PVWatts page—Results of the calculation.

The top number in Figure 2.13 (in this case, 425,046 kWh/year) gives the energy estimated to be generated in a typical year. The table then shows the values for each month. The "Solar Radiation" column indicates how much sunlight was found to be available in the solar resource data file for a surface of the specified orientation. The "AC Energy" column gives the electricity expected from the system. The "Value" column provides the product of the alternating circuit (AC) energy column and the price that the user specified as an input. The price for electricity will vary in different regions. If the costs vary by hour or by time of year, the user can calculate the price separately. The hourly simulation results can be downloaded by clicking the **Hourly** button on the final PVWatts page, as shown in Figure 2.14.

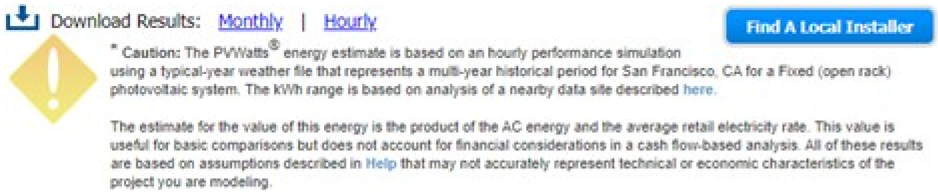


Figure 2.14. Download of PVWatts data in either monthly or hourly time increments.

A more powerful tool that allows for further fine tuning of inputs and results is the NREL System Advisor Tool available at https://sam.nrel.gov.

2.4 Understanding Uncertainty of Solar Resource

2.4.1 Weather Variability

The solar insolation measured year to year typically varies by about ±4 percent. Databases such as the Redbook, which can be found at the link given in Section 2.1.2, document this variability from year to year. In some locations and some data sets, the weather varies by more than ±4 percent. For shorter time scales, the variability is much greater.

2.4.2 Understanding Uncertainty in Ground-Based Data Sets

Carefully maintained ground-based meteorological data sets produce the most accurate solar irradiance data. Because the quantity of interest is measured directly, the accuracy is mostly dependent on the accuracy of the sensor, which may be accurate to a couple of percentage points. Thus, ground-based data sets derived from stations with state-of-the-art equipment that is cleaned and maintained on a daily basis have the highest accuracy data. These high-accuracy data sets are routinely used to calibrate terrestrial irradiance data derived from satellite data. Figure 2.15 shows a set of sensors, though these sensors would not be considered to have the highest accuracy.

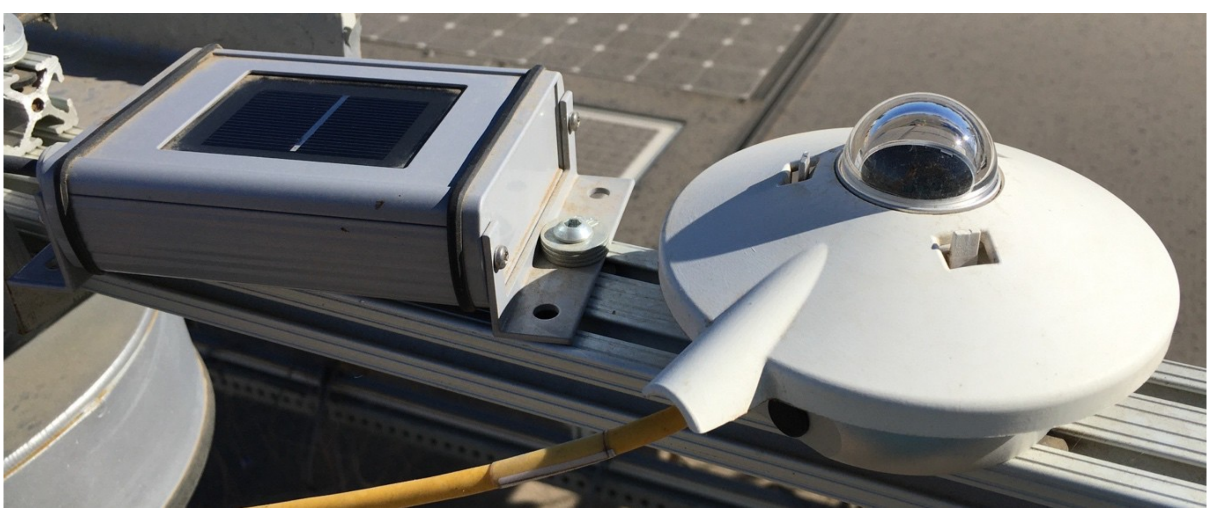


Figure 2.15. Example of reference cell and pyranometer mounted in same plane.

Ground-based irradiance data taken at solar systems often have much higher uncertainties. The accuracy of the sensors may be lower because the budget for equipping these systems is typically limited. A bigger source of uncertainty is often the limited cleaning or other maintenance of the sensors. As sensors are allowed to become soiled, the measurement taken by the sensor will be reduced. In some cases, this is intentional. In such cases, the solar system is usually also soiled. To compare the performance of a solar system with the measured irradiance, the sensor should be cleaned if the desired measurement is to include the soiling loss, or not cleaned if the loss of performance associated with the soiling is to be corrected from the measurement. Sometimes two sensors are mounted adjacent to each other and one is cleaned while the other is left to soil, providing a direct measure of the loss associated with the soiling, as shown in Figure 2.16. If the system requires substantial travel time to reach, the daily cleaning of the sensors can become cost prohibitive. In this case, it may be easier to attempt to correct the sensor data, if that is desired.

Figure 2.16. Sensors used to measure soiling.

As the reliability of satellite estimates continues to improve, and as demand for the finer spatial resolution possible with satellite-derived data increases, future national databases such as the National Solar Radiation Database will rely more and more on satellite data (Renné 2016).

2.4.3 Understanding Uncertainty in Satellite-Derived Data

Satellite-derived irradiance data have historically used empirical methods of correlating the satellite data with ground-based data. The accuracy of the data is very dependent on the timeframe that is studied. Today, satellite data may be recorded every 15 minutes, but older satellite data were more commonly reported once per hour. Thus, cloud movement is not described for the time during each hour. The satellite can record not only the image of the positions of the clouds but also other data, including ground reflection, temperature, and humidity. Satellite data that have been compared to ground-based data can be quite accurate over a year's time. However, for sites that have not been calibrated using ground-based data, errors of > 10 percent have been reported. In one study, calculations based on satellite-derived data were reported to overestimate the yield estimations of PV modules by up to 9 percent. In that case, the overestimation correlated with the mean number of cloudy days, and the study derived an empirical relationship to correct satellite-based yield calculations (Ernst et al. 2016). Comparing ground and satellite data to develop a relationship between the two for a location, coupled with ongoing collection of satellite data, is widely viewed to be the most accurate method for obtaining long-term irradiance data. Sometimes the largest errors are found for white-sand areas, for which it may be difficult to differentiate an image of clouds from an image of the ground.

The majority of data in databases today are derived from satellite data. The accuracy of these data is increasing as the sophistication of the satellite data increases and the algorithms for calculating the ground irradiance from the satellite data evolve, including use of existing ground-based data to calibrate the satellite data. The cost of gathering satellite-derived irradiance data is typically less than the cost of establishing and collecting ground-based data.

While the accuracy of state-of-the-art ground-based irradiance data is superior to the accuracy of satellite-derived data, today's satellite data can easily surpass the accuracy of many ground-based data sets, especially if the sensors are not carefully maintained (cleaned and calibrated). Thus, Caltrans may consider purchasing satellite data rather than investing in meteorological stations, though either may be expensive. Older irradiance data can be obtained for free online from NREL's National Solar Radiation Database or elsewhere.

Satellite-derived data are typically used in one of two ways: for a specific period of time, or to represent a summary of multiple years of data. Simply averaging the data from all years would miss representing the variability in the data, so data sets representing typical years have been assembled. These typical meteorological year (TMY) data sets are compiled by selecting the month that represents the median conditions for that location based on the multiyear data set. These are not "average" years, but "typical" years, and will not reflect extreme or anomalous weather. For more complete analysis of a site, the probability of high- and low-insolation years may be considered. For example, a P90 performance value may be calculated to represent the performance value that is expected to be exceeded 90 percent of the years.

3 SITE SELECTION

3.1 Available Solar Resource

As shown in Section 2.2, most of California has excellent solar resource. However, some locations are sunnier than others, with locations in southeastern California receiving roughly twice as much sunshine as the northwestern corner of California. This difference of a factor of two in sunshine can make a difference in determining whether a solar system is a cost-effective way to deliver electricity. Section 2 introduced solar resource concepts more generally. This section discusses some of the ways that site selection and system design can affect the electricity output.

3.1.1 Location of System—Assessing Solar Resource, Including Shading

As described in Section 2, the solar resource varies with location, and the relevant resource can be estimated from the maps shown in Section 2.2, the PVWatts calculator described in Section 2.3, or a number of other databases.

The site should be carefully assessed for local shading from both vegetation and manmade structures. The performance reduction is typically much greater than the fraction of the area that is shaded, so avoiding shade should be a priority. If shading from a nearby structure could be problematic, the performance loss should be modeled. Generally, shading near sunrise and sunset will have a small impact on performance and does not need to be considered because of the low output of the system at those times. Shading near midday is typically much more problematic. Shadows are cast in different locations at different times of year, so the assessment of shading losses should consider all times of year.

3.1.2 Size of System and Use of Performance Ratio to Estimate Output

A key consideration is selecting a site with sufficient size to accommodate the planned solar facility. The facility's size and layout should correspond to the space available in the right-of-way. Since the amount of land needed for an installation is related to the electrical capacity, it is important to consider the desired system capacity when selecting the size of the installation (IEC 2017). According to a guide from NREL, a 1-MW solar system installation requires a site with a minimum size of about 3.5 acres (Ong et al. 2013). In general, the profitability of solar projects increases as the amount of power produced by the site increases, and many solar developers prefer to be involved with projects of 1 MW or larger. However, if a project is designed to supply power for a local load, it may be attractive to size the system to meet the needs of that load. In particular, facilities such as rest areas and maintenance yards are potentially suitable for solar installation projects.

In general, the size of the system is the primary determinant of the output of a solar system. A simple estimate of the daily output of a system can be derived from:

$$\text{Electricity estimate (kWh/d)} = \text{System DC power rating (kW/(kW/m}^2\text{))} \times \text{Daily insolation (kWh/m}^2\text{/d)} \times 0.8$$

where the *system DC power rating* is the sum of the power ratings of the modules and the *insolation* is specific to the site and the orientation of the system (see next section). The 0.8 factor is often called the performance ratio and typically varies between 0.7 and 0.95. The observed performance ratios have been increasing with time as the module power ratings have become more conservative and other losses in the system have been reduced. Locations with higher temperatures can expect to exhibit lower performance ratios because of the decrease in efficiency of the solar modules with increased temperature.

Another key factor in determining the performance ratio is the DC-to-AC ratio. As discussed in Section 6.2.2, the DC rating is generally taken to be the sum of the module power ratings, while the AC rating is the sum of the inverter output power ratings. The sizing of the AC components (transformers and transmission line capability) need to meet or exceed the AC rating of the plant; otherwise, the output of the plant will not be able to be fully injected into the grid. As the cost of solar modules has decreased and the cost of the transformers and grid power lines has increasingly become a factor, system designers have begun adding more solar modules so that there are many times during a day when the output of the solar modules exceeds the capability of the inverter. When the output of the plant is limited by the inverter instead of by the solar modules, the inverter is said to "clip" the output (see Section 6.2). This clipping can result in the plant operating at its AC-rated power over much of the day. The performance ratio calculated from the DC power rating will decrease if there is substantial clipping. However, if the AC power rating is used in the equation, the last term may increase, with the 0.8 being replaced by a number closer to 1.

Thus, it is useful to consider both the sizing of the DC power rating (sum of the solar module ratings) and the AC power rating (sum of the inverter power ratings). The DC/AC ratio has been increased to 1.3 or 1.4 for many of today's systems. Systems being designed with battery storage may choose to use DC/AC ratios closer to 2. As an example, a plant with 100 kW of inverters might be attached to 200 kW of solar modules and 100 kW of batteries. During the day, half of the solar electricity is directed to the inverters to be put directly on the grid, with the other half directed to the batteries for storage. After the sun sets, the 100 kW of batteries then feed DC electricity into the 100 kW of inverters for injection onto the grid.

3.1.3 Orientation of System: Tracked versus Fixed

The sunlight captured by a solar module depends on its orientation. If a solar module is placed on a tracker and pointed directly at the sun at all times, it will receive more solar insolation than if it is fixed. However, tracking is often not chosen because there is (a) added cost in the tracker, (b) added maintenance requirements for the moving parts, and (c) adjacent solar modules that may shade each other if they are spaced too closely together. In general, the optimal solution has moved toward using one-axis trackers for large fields and fixed tilt for smaller installations, especially when mounting is on a building. The technology for the trackers is still evolving but has advanced rapidly, enabling their wide deployment. The row-to-row shading early and late in the day is often avoided by "backtracking." In this case, the tracker orients the solar modules so that they do not shade each other, accepting that this means that they are no longer perpendicular to the sun's direct beam.

Fixed systems in California are generally oriented to face south if the desire is to maximize the electricity generation over the entire year. However, capturing the late afternoon sun provides benefit because the electricity generation may better match the load profile if solar modules are oriented to face west somewhat. The row-to-row spacing of tilted modules must be modeled over the entire year to evaluate the trade-off of lower output associated with row-to-row shading relative to the larger footprint of the project when ample spacing is allowed.

A recent development is the possibility of mounting bifacial modules so that one side faces east and the other faces west. This could be of particular interest to Caltrans for sound barriers for north-south running highways. These systems would generate very little electricity at noon, when the sun is directly overhead, but they would generate more electricity near sunrise and sunset if there is not much local shading. This mounting orientation also has the benefit of reduced soiling rates. However, it only works well for highways that run north-south and is unlikely to be scalable in that only one row of modules can easily be oriented in this way, and it would be unwise to put them too close to the ground (because of shading) or too high from the ground (because of wind load), limiting the total power that could be generated. Figure 3.1 shows an example of bifacial modules used for noise barriers.

Figure 3.1. Bifacial modules for noise barriers. Image source: Solar Energy Application Centre, https://www.pv-magazine.com/2019/02/20/bifacial-modules-ridin-down-the-highway/.

3.2 Where Will the Electricity Go? Getting the Electricity to the Customer

Perhaps the most important consideration for any solar project is how the resulting electricity will be used. Much more important than choosing a location with good solar resource is choosing a location where there is a customer who wishes to use the electricity, as selling the electricity on the wholesale market is less likely to be cost effective. This study assumed that Caltrans would typically be the customer of the electricity, using it for energizing signalized intersections or other applications.

3.2.1 Possibility of Local, Off-Grid Application

Caltrans is already routinely deploying off-grid solar systems for powering intelligent transportation system (ITS) equipment in locations where the grid is not easily available. Thus, it was determined that the off-grid topic is mostly outside of the scope of the current study, so it is discussed only in a limited way. Battery energy storage systems attached to solar systems behind the meter are becoming more common and may grow in size. This trend is driven by three primary factors: (a) the falling cost of batteries, enabling a sizable battery bank at a reasonable cost; (b) the falling value of solar electricity on the grid; and (c) the public safety power shutdowns driven by risk of wildfires during times of high winds, motivating installation of microgrids for purposes of resilience. Indeed, the difference between on-grid and off-grid systems may be blurred as microgrids are developed to provide energy reliability in times when the main grid is shut off—for example, during high winds for fire prevention.

3.2.2 Grid Connection

The proximity of existing power lines may be the key driver of siting of many solar systems. If power lines do not exist near the selected site, new power lines will need to be installed. New power line installations are not only expensive but may also be difficult to permit, especially when power line installations are required across private property.

Power lines are typically differentiated according to whether they are designed for long-range transmission (an analogy would be a limited-access highway) using high voltages (60 kV–500 kV) or for distribution (with the analogy being local roads) using lower voltages (120 V–60 kV).[3] While it is possible to connect to either type of line, it is more likely that Caltrans will connect only to the distribution network. Permission must be obtained from the local utility (which is in charge of maintaining the lines and making sure that the grid functions well). Depending on the situation, the grid tie may be a fairly routine process or may require changes in the local grid hardware. A critical question is whether the existing wires are able to handle the additional load (see Section 3.2.3). In any case, a transformer is likely to be needed to adjust the voltage to match that of the power line. Because transmission lines operate at higher voltages, connections to them are more expensive.

3.2.3 Transmission and Distribution

When local generation and load are not balanced, the difference will need to be transmitted to the location where it will be used. Spare capacity will be needed on both the local distribution lines and any other distribution lines needed to deliver the electricity to a customer. Just as a highway is sized to service a given flow of traffic, a distribution line is rated to carry only a maximum current. In August 2020 during a time of hot weather, one of the emergency situations occurred when a transmission line coming from Oregon overheated and transmission needed to be reduced. Just as roads that were installed for a given traffic flow must be widened if traffic increases, the existing distribution lines might need to be upgraded if Caltrans asks to add electrical flow to a distribution line that is already operating near maximum capacity. As California installs more solar plants, it is becoming increasingly common for electricity to be curtailed because the lines are not adequate for transmitting and distributing the electricity to a load (Figure 3.2). Indeed, there are currently some days of the year in which California exports electricity to adjacent states. Curtailment is a useful tool when attempting to balance supply and

[3] For a description of how PG&E differentiates transmission from distribution, see https://www.pge.com/en_US/safety/yard-safety/powerlines-and-trees/transmission-vs-distribution-power-lines.page.

demand, but it is undesirable from the perspective of the solar plant owner, though preferred to selling the electricity at a negative price, which happens frequently in some of the electricity markets in California today.

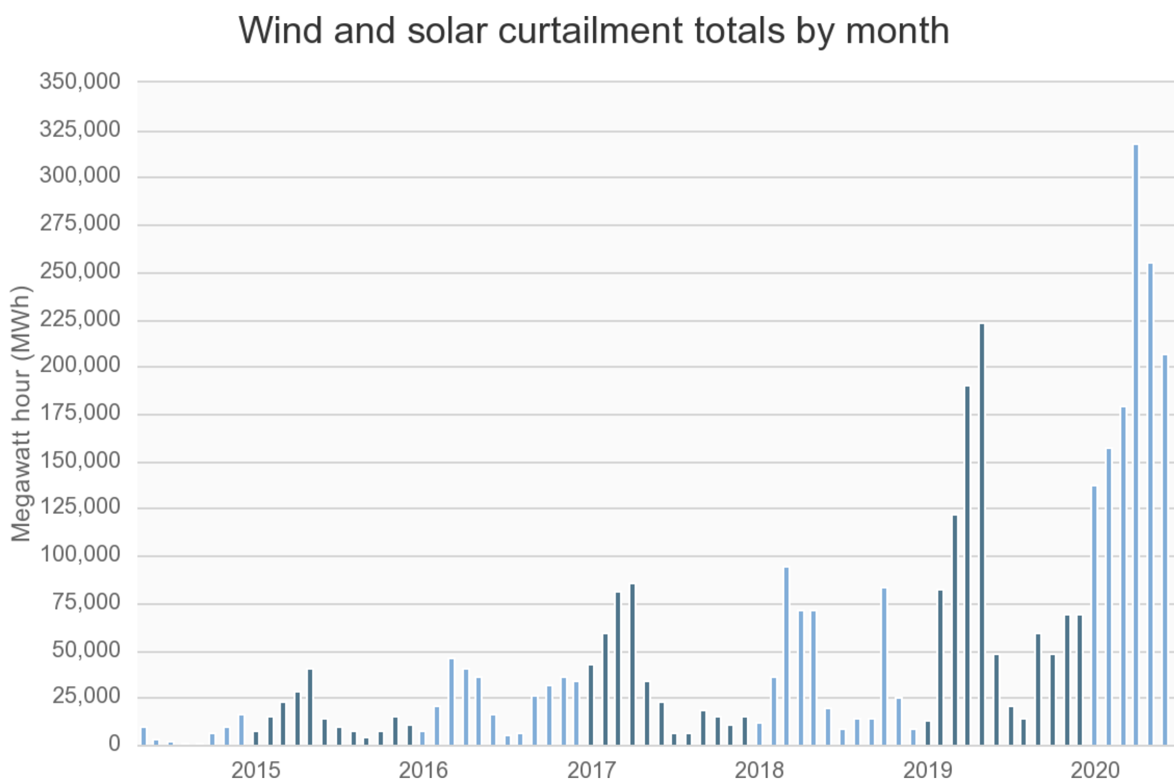


Figure 3.2. Curtailment of wind and solar electricity for the grid managed by California Independent System Operator (CAISO). Figure source: http://www.caiso.com/informed/Pages/ManagingOversupply.aspx/.

When considering the transmission of the excess electricity on the grid, it is important to note that the addition of a solar system to the grid may also be complicated by two-way electricity flow. The electricity grid was designed for one-way electricity flow from a central power plant to the customer. The voltage droops as the power flows away from the plant, but the customer expects to receive electricity with a constant voltage regardless of location. The grid has historically been designed to adjust for this droop in voltage. The addition of distributed solar systems results in electricity sometimes reversing directions. Thus, the power line that previously had lower voltage at its end might now have a higher voltage during the day when the solar system is feeding electricity into the grid, and a lower voltage at night when the electricity is flowing only from the central power plant. Technology has been developed to help maintain constant voltages at all locations on the grid, but the addition of a new solar plant may have some cost associated with replacing the hardware designed for one-way electricity flow with hardware designed for two-way electricity flow. The utility will evaluate these issues before issuing the permit for connecting and injecting electricity onto the grid.

3.3 Practical Considerations

3.3.1 Safety and Security

Primary safety and security risks for solar systems include the following:

- Harm to humans may occur as a result of electrical shock or arc flash, or by mechanical means during construction or disruptive weather.

- Fire can ignite by arcing in the solar system.

- Vandalism to the system may occur.

- A secondary risk is associated with the solar system interfering with firefighters extinguishing a fire.

- Solar systems with battery storage have additional safety risks. For example, see Colthorpe (2020).

- Solar systems located near moving traffic will have unique requirements. These have not been well documented, but a vehicle that enters a solar system at high speed will likely damage the system, potentially resulting in exposed electrical connections and creating broken glass, among other physical damage. Most solar systems in use today that are close to a highway are protected from vehicle ingress by barriers or sufficient setbacks.

- Sandwiched between the protective glass, frame, and backsheet of the solar module, the solar cells present no health risk, but burning modules may present a health risk because of chemicals released during combustion of the backsheet. Also, broken modules may leach lead, cadmium, and/or tellurium, depending on the module design.

In California, the risk and potential liability associated with starting a fire is unusually large because even a small fire can turn into a large fire that can kill people and destroy billions of dollars of property. Fortunately, just as today's buildings have very low risk of fire when built to code, solar systems have very low risk of fire when built to code and carefully maintained (see Section 6.3). However, fires do occur, so when siting a solar system, Caltrans may want to avoid installing solar systems in regions with a combination of high winds and readily available fuel source.

Primary risks associated with solar modules include electric shock and electrocution. While solar modules are exposed to light, they produce potentially lethal DC electricity. Thus, anyone working near a solar system during daylight hours should be aware of this potential hazard and should use standard personal protection equipment and procedures for the rated DC voltages. New products are being developed to safely shut down the solar PV system, reducing the voltage at the module level. Solar systems can be designed to be safe for people to touch and sit on, but such systems should be periodically inspected for any damage that could create a shock hazard.

Although solar systems are designed to fully contain hazardous electrical voltages, it is generally better if the local population is not able to access the system, both for safety reasons and to avoid vandalism. If a site that cannot use a fence to limit the access is chosen, the design of the system may be adjusted to reduce risk by using lower voltages and hardware designed for use in public locations.

It is common practice to install a fence around any solar system to prevent access by unauthorized personnel. It is less common to install alarms or video monitoring, but these may be useful tools to discourage both people and animals. If security lighting or video monitoring is installed, it should be included in the original design. One large installation in Colorado installed a multi-megawatt solar system, and then later installed a security system. The installed security-light poles partially shaded the solar modules during the day, resulting in substantial loss in power generation. When a site is chosen, space should be left for a fence (far enough from the system to minimize shading), and the need for installing security monitoring should be evaluated.

When adding batteries to solar systems, it is important to consider that battery code requirements may vary. For example, code requirements related to batteries have substantially delayed projects in New York State (Lempriere 2020).

Obviously, systems should be located so as to minimize the chances that vehicles will accidentally enter the area of the solar system. Caltrans' well-developed procedures for defining a safe zone may be the best guide, with consideration for planned road expansions.

3.3.2 Future Plans Regarding Site Selection

It is important to remember that a solar system is typically planned to last for 25 years and might end up lasting 50 years. If the highway is planned to be widened or otherwise modified, it would be better to choose a different site.

A difficult consideration to assess may be the possibility of growth of trees or construction of tall buildings nearby that might shade the system. If there is a possibility of nearby development, the potential impact on performance should be modeled.

3.3.3 Site Preparation Requirements (Drainage, Grading, Landscaping)

Most solar systems are mounted on level areas, but a south-facing or west-facing slope can also be chosen. The performance of a system is greater when each string of modules is oriented in the same way so as to capture the same amount of sunshine. While it is possible to adjust racking systems for uniform orientation of modules when the ground is uneven, doing so adds to the cost of the installation.

A solar system may be damaged by standing water, so siting in flood zones should be avoided. If flooding is infrequent and shallow, it may be possible to design the system to avoid damage, providing good use of land that is otherwise of little value.

It is strongly preferred to not have vegetation growing around a solar system, so it is best to identify a site that may be vegetation free rather than a site that is expected to be attractively landscaped. Otherwise, there will be a cost to regularly mow and maintain the vegetation. In at least one case (Florida), the DOT significantly underestimated these costs.

3.3.4 Site Access

The site should be easily accessible, preferably from a local road, not a limited-access road. In particular, systems that will require frequent access for vegetation control should have appropriate access that does not cause safety issues or added cost.

3.3.5 Glint and Glare

Near sunrise or near sunset, the sun will be reflected off solar modules at a glancing angle. While solar modules are made to absorb the visible light that strikes them, like a lake's surface, there may be a reflection when the light strikes the surface at a glancing angle. Just as the setting or rising sun can blind a driver, this reflection can blind a driver. While highways are usually not engineered to avoid the possibility of drivers driving directly into the sun, it is recognized as a hazard that can cause accidents. In the case of a solar system, glint and glare may surprise a driver and cause complaints from the public. In contrast to the inability to avoid driving into the sun on a highway, it is sometimes possible to orient a solar system to avoid this problem. Sandia National Laboratories has developed tools to assess potential issues with glint and glare. These can be accessed at https://share-ng.sandia.gov/glare-tools/.

3.4 Financial Considerations

The requirement of payment of a fair value for use of the land will increase the cost of deployment of systems in urban areas, motivating the choice of rural sites.

Financial considerations were discussed in detail in the Task 6 report, *Financial Opportunities Assessment*, and are not discussed again here other than to emphasize the importance of identifying a site that is consistent with the business model.

4 PROJECT STAGES AND MANAGEMENT

The literature review and follow-up interviews with DOTs involved in the development of solar projects found that each solar project has both elements that are unique and elements in common with other solar projects. Based on the synthesized information, the researchers offer guidance in this section that highlights important stages in the development of a solar project, recommendations for each stage, and ways to avoid common pitfalls. Important stages include site selection, contractor selection, design review, construction oversight, mechanical commissioning, electrical commissioning, initial performance test, ongoing performance tests, and system design and operation documentation. This section further highlights recent and ongoing efforts to standardize solar project design.

4.1 Standardization of Solar Projects

The solar industry is a young and rapidly changing industry. As the industry matures, solar system design, contract negotiation, and implementation will all likely become more standardized. Ultimately, solar systems must comply with local building codes, reflecting local requirements to address local hazards such as risk of wildfires and earthquakes. However, the solar industry is now a global industry, with some companies installing systems globally. To the extent that it is possible and appropriate, there is value in harmonizing the local standards with international standards. For many years, the U.S. safety standard for module design qualification, *Standard for Flat-Plate Photovoltaic Modules and Panels* (Underwriters Laboratory [UL] 1703), was not standardized with the international version, resulting in manufacturers selling two versions of their product, with the version sold into the U.S. market being required to pass a safety test and the international version being required to pass both a safety test and a qualification test that ensured that most of the initial performance was retained after stress was applied. While Caltrans will need to follow local code requirements, it may choose to support the industry's efforts to move toward harmonization of local standards with international standards. This section on project management attempts to guide use of such standards, but it is not comprehensive. Caltrans might consider identifying an individual to engage in standards development to represent the customer point of view, which is typically underrepresented in the standards development process. Not only would this involvement be beneficial to the larger community, but Caltrans would then be one of the first to hear of reports of problems identified with new products. Standards organizations are summarized in Appendix A, along with information about how to join each organization.

4.1.1 Value of Standardization

Much of the improvement in quality and reduction in prices for both solar modules and solar systems has been a direct or indirect result of standardization. The standards are far from mature, but reference to standards during project implementation can be key for cost-effective implementation of high-quality systems. Nevertheless, at the industry's current stage of development, standardization is challenging and even inappropriate in some situations. An example of where standardization is not yet appropriate is in the physical dimensions of modules. Customers would like to be able to replace any broken module with a new module, just as a burned-out light bulb is replaced with most any new light bulb. There are two reasons why this has not yet been standardized. The first is that the industry is still innovating new module designs. For example, a new frame style that reduces labor during an installation process or a frame style that removes the need for racking can lead to reduced cost. Standardizing a current design that will ultimately be more expensive is not in the best interest of the community. The second reason has to do with optimal functioning. A replacement module needs to not only match the physical size of the old module but also deliver a similar current and voltage in order to function well in the larger circuit. As modules are becoming more efficient, the current and voltage for the same size module are increasing, making a drop-in replacement difficult to standardize at this point. Ideally, manufacturers will continue to improve module efficiency in such a way as to avoid the need to standardize the size or current/voltage output.

4.1.2 International Efforts at Standardization

IEC writes standards that guide solar module qualification and implementation. The vast majority of solar modules manufactured today use IEC standards for design qualification and testing. In particular, certification to IEC 61215, *Terrestrial Photovoltaic (PV) Modules – Design Qualification and Type Approval*, and IEC 61730, *Photovoltaic (PV) Module Safety Qualification*, will be found almost universally. The IEC has written more than 100 other solar-related standards. The utilization of many of these is less consistent, often with implementation only at the request of the customer.

IEC works in partnership with the International Organization for Standardization (ISO) as well as the IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE) in the implementation of the standards. In short, IEC writes technical standards and ISO and IECRE guide implementation of those technical standards. A table of existing standards written by IEC and others can be found in Appendix B.

There are additional international standards organizations developing standards relevant to the solar industry. For example, SEMI, formerly called Semiconductor Equipment and Materials International, writes standards related to the purity of the silicon feedstock that is used for making solar cells. Appendix A highlights the work of a few of these organizations.

4.1.3 U.S. Efforts at Standardization

Close to a dozen standardization efforts touch on solar systems within the United States. These range from local codes to national codes. A summary of some of these organizations is included in Appendix A.

The National Electrical Code (NEC) is a key resource for local codes that are implemented by the authority having jurisdiction (AHJ). Most countries around the world use standards developed by the IEC Technical Committee (TC) 64 as the basis for their local electrical codes. The United States interacts with IEC TC 64 but has maintained a level of autonomy in setting its code requirements. The NEC is focused on safety, including safety with respect to preventing fires as well as personal injury from electrical shocks and arcing. The NEC is part of the National Fire Protection Association (NFPA) 70 Code. In recent years, much of the PV discussion in the United States has pertained to concern for firefighters who might be asked to fight a fire in a building with a solar system on the roof. Firefighters have requested that they be able to flip a switch and eliminate or at least reduce the voltage within a solar system so as not to accidentally encounter high voltage while fighting a fire. While the topic of shutting down rooftop solar systems is not directly relevant to putting solar systems in diamond and cloverleaf intersections, Caltrans could envision similar concerns from emergency response personnel responding to an accident or fire that could involve close proximity to a solar system.

UL defines safety standards for electrical components within the United States. During a multiyear negotiation, most of the IEC and UL standards have been harmonized, with only a small number of national differences identified for most standards related to solar modules. Certification to UL 61730, *Photovoltaic (PV) Module Safety Qualification*, is required for most modules purchased in the United States.

The Institute of Electrical and Electronics Engineers (IEEE) was actively developing standards for solar systems in the 1990s but united its efforts with IEC when the solar market expanded in Europe, resulting in the IEC standards being the accepted standards for solar modules worldwide. On the other hand, the standards for grid operation are defined regionally, and IEEE 1547, *IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems*, defines how solar systems connect to the grid. Initially, the strategy was to disconnect the solar system from the grid if any problem developed. However, as the fraction of electricity coming from solar energy grew, it was found that programming the inverters to disconnect from the grid if the frequency dropped below a certain threshold could result in a small variation of the grid frequency, turning it into a much larger problem since disconnecting gigawatts (GW) of power from the grid just at the moment when the frequency is drooping exacerbates the problem. Instead, solar systems are now viewed as potentially useful tools for providing ancillary services for the grid, including frequency support, spinning reserve, and non-spinning reserve. Concerns have been raised about the quality of the electricity on a grid supplied primarily by solar electricity because of the need for a transition from a centralized electricity source, where electricity flows in one direction (from the power plant to the customer), to one in which electricity may flow both directions and in which non-synchronous generators may provide the majority of electricity. It is now understood that solar systems can provide solutions. Thus, the latest version of IEEE 1547 defines how inverters can help stabilize the grid rather than how inverters must disconnect if there is any problem.

While it is essential that IEEE 1547 define robust interconnection with the North American electrical grid, there is also value in keeping standards harmonized with the international standards in order to improve all components. Just as solar modules are manufactured and sold within a global market, inverters are also mostly supplied on a global market, often with jumpers that can be configured for use on different continents so that manufacturers can focus on manufacturing a reduced number of products. Nevertheless, grid-connection standards within the United States are typically based on IEEE standards, with local requirements for permitting to meet the technical requirements. The complement to the IEEE standards being developed in the United States for how inverters function is at least partially occurring internationally within IEC TC 82.

4.1.4 Project Timeline with Standards Overview

An overview of the multiple steps in a project timeline and the available standards for guiding those steps (Kurtz et al. 2017) is shown in Figure 4.1. The remainder of Section 4 describes some of the most important details shown in Figure 4.1. The standards are described in the appendices.

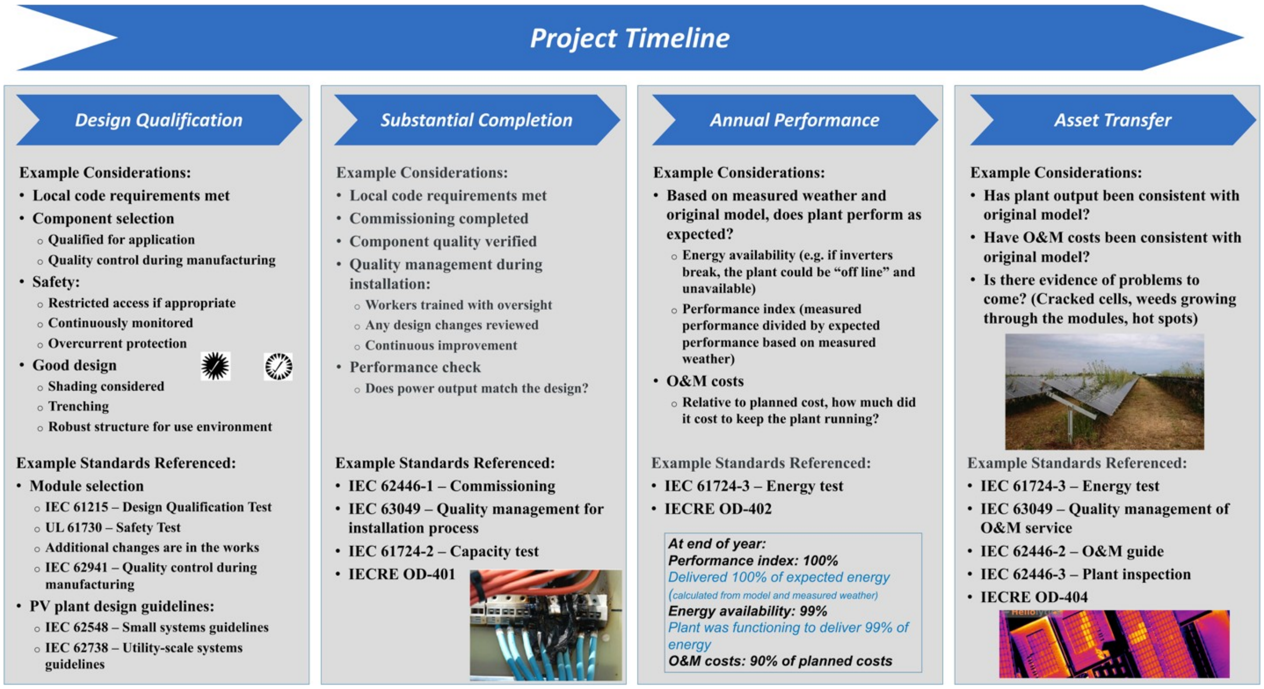


Figure 4.1. Project timeline and associated international standards.
Figure source: Kurtz et al. (2017).

4.2 Site Selection

Site selection is ordinarily completed (or at least initiated) at the concept stage of a solar project. Key considerations for site selection are summarized in Section 3. This important, and often time-consuming, step may be completed by Caltrans, by a consultant through a bid process, or by a combination of the two.

4.2.1 When Caltrans Should Select the Site

In general, it will make sense for Caltrans to install a solar system when it has a need for the electricity. Based on Caltrans' identified need for the electricity, the site selection process will be more easily focused on a location well suited for meeting that need.

The work required to define a site for a project can be quite significant. Companies will not want to spend the time to research available sites, so more companies may bid on projects if at least some of the upfront selection work has been completed. Companies will appreciate having information supplied about access to a grid connection, availability of a local customer for the electricity, condition of the current site, and so forth. In the majority of cases, the researchers anticipate that it will be useful for Caltrans to either select a specific site or narrow the options, much as any organization would do when selecting a construction site.

4.2.2 When a Caltrans Partner Company Should Select the Site

There may be times when builders would prefer to select the site—for example, if they will have ongoing operations and maintenance (O&M) responsibility or if they have a preferred style of installation that may work best in a specific geometry. Also, there is the possibility that if Caltrans announces that it is open to hosting systems, developers who are exploring projects in the area may also look at sites on Caltrans property.

4.3 Installation Contractor Selection

In general, installation contractor selection should follow procedures for any major construction project: it should be based on the installation contractor's reputation, including strong references from previous customers, multiple years of experience, certification with the local AHJ, and solid business (financial) standing. Previous experience with Caltrans is a plus, especially if previous contract terms can be duplicated. Additional considerations when selecting an installation contractor for a solar system include:

- The installation contractor is actively installing solar systems at a rate that allows negotiation of large purchases of solar components, enabling improved quality control at an affordable cost as well as early warning if a problem develops.

- The installation contractor should negotiate for quality control as part of procurement negotiations. For example, module manufacturers are typically more conservative in assigning nameplate ratings if the contract will apply a penalty or bonus based on independent verification of the nameplate ratings. Modules purchased through a distributor typically are of lower quality than the same module procured directly from the manufacturer but through a robust contract. For example, manufacturers may choose to label a module as 300 W instead of 320 W if the purchase contract includes a penalty for the modules underperforming. The manufacturer evaluates the probability that the purchaser of the module will send the module to a test lab and find that it generates 310 W. In this case, the manufacturer may prefer to receive a lower price for the 310-W module sold as 300 W than risk the penalty incurred if the 310-W module is labeled to generate 320 W.

- The company has tracked output for multiple years and updated its installation processes based on identified problems. Some customers refuse to share data, so lack of 100 percent of previous systems being documented should not be a red flag, but historically, it has been demonstrated that companies provide better results when they have tracked outcomes from previous construction and worked with customers to negotiate a strategy for tracking outcomes by explaining to the customers why doing so is important. While logically this makes a lot of sense, there is an added cost associated with this after-the-fact quality control, so companies differentiate themselves by how much attention they pay to the outcomes of their previous work.

- There is value, both in reduced costs and in increased experience, when a company is able to leverage a design that has been installed elsewhere with only small changes to enable the standard design to fit the new site.

4.4 Design Review

Design review may be guided by IEC 62548, *Photovoltaic (PV) Arrays – Design Requirements*, and/or IEC/TS 62738, *Design Guidelines and Recommendations for Photovoltaic Power Plants*. The information presented in Section 6 reviews many design considerations, so these are not repeated here. This section provides complementary information about warranties and quality control.

4.4.1 Warranty and Liability Review

Selected equipment warranties should be reviewed in detail. Most solar module manufacturers offer a 25- or 30-year limited warranty, but these may be of limited value, depending on the details of the warranty. Typically, the warranty for product workmanship is for a much shorter time. The 25- or 30-year limited warranty often refers only to the performance. However, demonstrating that the performance has dropped below the warrantied value often requires measurement at a professional test laboratory. Also, the manufacturer may no longer be in business to service a warranty claim. Some manufacturers have insurance to cover the warranty for the customer in the case that the manufacturer itself is not solvent at the time of the warranty claim. While reading the fine print on the warranties is part of due diligence, working with companies that pay close attention to quality control to avoid the need for a warranty claim is even more valuable.

Warranties for inverters and other power-conditioning equipment are also critical given that the majority of failures associated with solar systems are reported for the inverters and other non-module components. Equipment designs are changing rapidly, and the testing for inverters and other power-conditioning equipment is quite challenging. Failure of an inverter is much worse than failure of a module because it typically shuts down many modules or even the whole system. Even worse, repair of an inverter can take months. Some customers specify a service contract that ensures the service for inverters will be provided within 48 hours since warranty replacements may not be viewed as time critical by the manufacturer.

It may be useful for the warranty to be written in such a way that all components within a range of serial numbers will be replaced if similar components are found to be defective in other solar systems.

Additionally, the warranty may depend on ownership and may be affected by installation. Misalignment of the system design and implementation with the manufacturer's guidelines may void the warranty. For example, the degradation rate of some thin-film modules has been reported to be accelerated when the modules sit in the sun at open circuit (e.g., not connected to a system), so a delay between installation and commissioning could be problematic. Caltrans should review start and end dates for each component's warranty as well as the business relationships that could affect accessing warranty replacement, if that is needed.

Clarification of liability, to the extent possible, is always useful. When a failure occurs and the manufacturer and installation contractor disagree on who is to blame, the matter may end up in court before the system is returned to working order. While such situations are rare, it may be advisable and less time consuming if the installation contractor takes responsibility for a working system with the ability to directly access the manufacturers' warranties.

4.4.2 *Quality Control*

As standard for any project, all equipment and designs should be consistent with local codes and standards. In addition, solar module designs should be certified to UL 61215 (IEC 61215) for design qualification and UL 61730 (IEC 61730) for safety. Inverters should be certified to UL 62109 (IEC 62109), *Standard for Safety of Power Converters for Use in Photovoltaic Power Systems*, for safety; IEEE 1547 for grid compatibility; IEEE 519, *IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems*, for harmonics; and UL 1998, *Standard for Software in Programmable Components*, or similar for software robustness. For quality control, Caltrans may consider the common ISO 9001 and related standards. However, newer quality control standards are available and will be adopted when customers start to ask for them; specifically, IEC 62941, *Terrestrial Photovoltaic (PV) Modules – Quality System for PV Module Manufacturing*, provides quality control related to the product delivering the performance described by the data sheet in addition to ISO 9001, *Quality Management Systems – Requirements*, for modules. IEC 63157 provides a similar role for inverters and other power-conversion devices. These are strongly recommended but currently are not considered to be standard certifications.

Many-MW or other elite customers require a more thorough analysis that includes extended-stress testing of the module design (with specific bill of materials that will be used for manufacturing) and batch testing of a subset of modules pulled from the procured production lot. Such testing and engineering analysis are too expensive to be included in small procurements. Some installation contractors form buying consortiums so that they can cost-effectively source high-quality modules.

IEC 63209, *Extended-Stress Testing of Photovoltaic Modules for Risk Analysis*, is being developed as an extended-stress testing protocol for gathering data to inform an engineering analysis. It is not meant as a pass-fail test, but it may provide a tool for assessing the quality control by identifying whether randomly selected modules show similar retention of original properties after extensive stress.

Newer module designs and newer components merit more careful review. In particular, the requirements for batteries coupled with solar systems are rapidly evolving. Special care is needed to avoid fires with batteries. The guidelines and standards for inclusion of batteries are not yet in the mainstream.

Quality control is important, starting with the design and selection of components that are manufactured under carefully controlled conditions. Then, quality control continues to be important at every step, including manufacturing, installation, operations, and maintenance.

4.5 Construction Oversight

As with most construction projects, inspections should be conducted during the construction project as well as upon completion. IEC 63049, *Terrestrial Photovoltaic (PV) Systems – Guidelines for Effective Quality Assurance in PV Systems Installation, Operation and Maintenance*, identifies key elements to track during construction. Examples include inspection of trenches before being covered and day-to-day records such as documentation of worker training and for equipment calibration and inspection.[4] IEC 63049 is a relatively new standard and is not widely used. Most established companies created their own version before IEC 63049 was published in 2017. In the future, there may be value in standardization of these oversight procedures.

The local AHJ and/or Caltrans must inspect during construction to ensure compliance with local codes.

4.6 Mechanical Commissioning

Commissioning of the mechanical construction is usually completed before the completion of the electrical commissioning, though the two may be completed together in some cases.

The mechanical commissioning is likely to be similar to what Caltrans does routinely: confirm that the construction followed the design (or deviations were documented and justified) using the specified components with the specified certifications.

Local codes may differ and may not be fully developed regarding appropriate controls for localized concerns such as earthquakes and mudslides. This study did not include these. In general, solar systems deployed in locations with high winds require an engineering review.

4.7 Electrical Commissioning for Plant "Turn On"

Electrical commissioning is usually completed as a separate step before the initial performance test. IEC 62446, *Photovoltaic (PV) Systems Requirements for Testing, Documentation and Maintenance*, describes standard procedures. If quality control during construction has carefully followed IEC 63049 (see Section 4.5), very few problems may be found. Manual testing of every string in a large solar system may be quite time consuming, but it is obviously useful to confirm that strings of modules have not been connected with the wrong polarity, and so forth.

4.8 Initial Performance Test (Capacity Test)

The electrical generation from a solar system is dependent on the weather conditions (such as the irradiance, ambient temperature, and wind speed, with smaller dependence on the solar spectrum and angle of incidence of the light). Demonstration of the performance specified by the contract typically involves a capacity test, often over 3 to 10 days, with data collection throughout each day. In general, characterization of a solar system is complicated by inadvertent bias; for example, irradiance, ambient temperature, angle of incidence, and the solar spectrum are typically correlated with each other.

IEC 61724-2, *Photovoltaic System Performance – Part 2: Capacity Evaluation Method*, provides a robust approach that was originally developed by SunPower and then adapted as an international standard by IEC. It suggests that module temperature should be derived from the measured ambient temperature, irradiance, and wind speed and that the measured output is

[4] An example of a case where the oversight was lax was a story told by an industry veteran about when a new worker did not understand the importance of using a torque wrench when tightening electrical connections. Another worker noted the improper procedure, and the new worker started using the torque wrench but did not go back to check the connections at the previous site. A few weeks later, that system experienced an electrical fire.

adjusted for variations in irradiance and module temperature for comparison to the expected plant output at a predefined set of conditions.

A linear regression method for characterizing the output of a solar system was developed in the 1990s under the Photovoltaics for Utility Scale Applications (PVUSA) program in California. It has been adopted as a standard by the American Society for Testing Materials (ASTM) (E2848). The method calculates coefficients of performance using a linear regression to fit the measured power output to a function of the measured irradiance, ambient temperature, and wind speed. This is a simple approach, but it tends to have higher uncertainty (greater weather dependence) than IEC 61724-2, especially if the reference test condition requires an extrapolation. ASTM developed a methodology of identifying the test conditions in such a way as to avoid extrapolations. This improves the accuracy of the application of the ASTM approach but requires definition of multiple test conditions to prepare for tests that might occur at different times of year, complicating the initial contract. While the industry is likely to eventually settle on the IEC methods because of their inherent values and for the benefit of international standardization, many U.S. companies are still using the ASTM approach, and Caltrans may find it easier to accept the established protocol than to insist on making the transition.

4.9 One-Year or Ongoing Performance Testing (Energy Tests)

The initial capacity test is typically used to confirm delivery of a system that is working, enabling payment to be completed. However, for large systems, the contract may specify that a final payment will be made based on confirmation of a full year of performance data.

There are some errors that may not show up in the short test but will be found in the year-long test. For example, if rows of solar modules are placed too closely together, nearby rows may shade each other, reducing power output during times when the sun is low in the sky (such as in the winter). Additionally, variations in operating temperature may cause the voltage to drift outside of the inverter operating window. Some inverters may reduce their power capability if they overheat, which may only happen on the hottest days of the year. Many other issues may potentially surface over the course of the first year of operation. Depending on the available funds, the year-long test may be very detailed (to be very accurate) or be very simple (to be economical, e.g., comparing the electricity generated at the end of the year relative to the expected electricity).

IEC 61724-3, *Photovoltaic System Performance – Part 3: Energy Evaluation Method*, defines a procedure for quantifying the output of the system relative to what would be expected according to the contract and the observed weather. IECRE OD-402, *Annual PV Plant Performance Certificate*, gives an example of a certificate that can be given based on implementation of IEC 61724-3.

4.10 System Design and Operation Documentation

The life of a solar system is anticipated to be 25 years or longer. The as-built designs and initial performance documentation will be useful for multiple future situations, including if the system is sold or refurbished. The original designs are typically modified to incorporate the hardware that is available at the time of construction. Solar technology is evolving rapidly enough that it is quite common for the solar modules used for the final construction to differ from those of the original design. IEC 62446-1, *Photovoltaic (PV) Systems – Requirements for Testing, Documentation, and Maintenance – Part 1: Grid Connected Systems – Documentation, Commissioning Tests and Inspection*, provides guidance on documentation recommended during the commissioning process. Documentation during operation is discussed in the following section.

5 PLANT OPERATION AND MAINTENANCE

5.1 Planned Maintenance

Solar systems are known for requiring very little maintenance, but execution of appropriate maintenance can avoid significant damage to a system. The required maintenance varies depending on the location and the design of the system. Some maintenance items that may be required include:

- **Servicing Inverters.** Regular preventive maintenance of solar inverters throughout their lifetime ensures maximum availability and minimum unplanned repair costs. These typically include tasks like cleaning or replacing fan filters, lubricating fans, removing any debris, and checking the sunshade to ensure that the inverter is not overheating.

- **Cleaning Arrays.** The solar modules should be cleaned whenever the increased electricity generation will offset the cost of the cleaning. Some systems may be damaged by the partial shading that occurs during cleaning, so it is important to follow the manufacturer's guidance. However, reports from several states indicate that their solar modules were essentially self-cleaning, requiring very little or no cleaning at all. Some jurisdictions consider the effluent from the cleaning to be hazardous waste, complicating cleaning procedures.

- **Maintaining Trackers.** The moving parts of the solar trackers typically require some lubrication, which should be applied according to the manufacturer's recommendations.

- **Controlling Vegetation.** Grasses and other plants growing around the array might cause shading that reduces electricity generation and can increase solar module degradation.

- **Controlling Wildlife.** Birds, ants, and other wildlife may leave debris or make nests in undesirable locations. Inverter housings should be sealed to prevent small animals from entering the housing. Sealed junction boxes and conduits can prevent damage by insects and rodents.

- **Conducting Visual Inspections.** Visual inspections on a recurrent schedule may identify damage to wiring, loose fittings and cables, corrosion of grounding paths, or other problems. Infrared camera inspections can identify electrical connections that are increasing in resistance.

- **Installing a Weather Station.** A weather station can help monitor local climate conditions that might help identify potential issues with the solar project. However, a weather station used for gathering data might require frequent planned maintenance, including daily cleaning. It may be possible to adapt Caltrans Road Weather Information Systems (RWIS) data to provide useful reference data.

IEC 62446-2 describes maintenance procedures and the documentation that should be kept. The frequency of these inspections should be adjusted based on past experience. For example, it may be found that the modules should be cleaned once per year after harvest, or it could be most useful to execute the visual inspection in the spring when wildlife are building their nests. As an initial plan, it may be best to duplicate the plan for a nearby system. This might also help the company maintaining the system, which needs to coordinate and stagger maintenance plans to optimize performance and cost.

5.2 System Monitoring

Monitoring of the system output is critical for many reasons, including that any problems can be quickly identified, projections can be made for the future, and the value of the project can be assessed. Solar systems that make use of PPAs are typically monitored remotely by the project developer. Systems owned by the DOT should also be monitored. In the past, the lack of system monitoring in a DOT-owned solar system resulted in the DOT being unaware that the solar system had stopped producing electricity for several months.

5.2.1 System Monitoring for Long-Term Project Assessment

The quantities of electricity that may be measured are defined in IEC 61724-1 and are discussed from different points of view in Sections 4.8, 4.9, and 6. Depending on the size of the system and the value of the electricity being generated (which usually determine the available budget), a high-accuracy or low-accuracy test may be appropriate. In general, IEC 61724-2 and/or IEC 61724-3 may be applied at any time. Recommended practice is to apply IEC 61724-2 anytime there is suspicion of a problem and to apply IEC 61724-3 annually. If data are collected continuously and an IEC 61724-3 annual energy test is applied once per year, the resulting record is valuable to identify the ongoing status of the system. IECRE OD-402 is designed to document this information on an annual basis. The test may be so simple as to only record the annual energy, or for large systems, the test may involve a full weather station to fully document the weather, including the irradiance in the plane of the array, ambient temperature, and wind speed/direction recorded at an hourly or shorter time interval. In general, purchasing weather data (as derived from satellites) may be less expensive (though lower in temporal resolution) than maintaining a weather station.

At the point of asset transfer (either at the end of a contract or through a new sale), it is good practice to assess the status of the system. IECRE OD-404, *PV Plant Operational Status Assessment*, is designed for this purpose. It not only assesses the past performance and current status but also attempts to project future performance.

5.2.2 System Monitoring to Identify Faults, Including Risk of Fires

Monitoring the daily output of a system can enable action to provide very prompt service for a system. The most frequent fault is with inverters, which may require power cycling, just as a computer sometimes requires a reboot. Solar systems that are not monitored and not routinely inspected are often found to be offline with a simple fix of restarting the inverters.

A critical concern for Caltrans is to avoid any electrical problems that could cause a fire. As described above, a robust quality control program is the first line of defense for avoiding fires. However, it is important to note that thermal cycling and general aging of components can sometimes lead to electrical fires. During annual inspections (or any inspection triggered by an anomalous observation or extreme weather event), an infrared camera should be used to look for evidence of unexpected heating. All electrical connections should be included in the inspection. If a connection is increasing in resistance, it may show localized heating before getting hot enough to be damaged. Note, however, that it has not been documented that all such failures show evidence of heating in advance of full failure. Caltrans may also wish to spot-check systems to confirm that electrical connections have not changed. For example, in general, a torque wrench is used to tighten certain types of electrical connections to ensure adequate tightness without overtightening. If thermal cycling causes some of these connections to loosen with time (or if some connections were not tightened correctly in the first place), spot-checks could identify potential problems.

While increased resistance in a connection can be problematic, fires can also be caused by arcing. These problems may be more difficult to detect because they may depend on the level of moisture or other conditions. There are two kinds of DC arcs: parallel and series. Ground faults and shorted wires are examples of parallel arcs. Open circuits, particularly in the modules, are examples of series arcs. Today's inverters are designed to detect ground faults and to shut off operation if a ground fault is detected. Identifying the right threshold for this safety feature has been a challenge—if the threshold is set too low, the inverters may trip frequently for situations that are not actually problems. Frequent nuisance trips then become confused with real problems. An inverter that will not operate because of a ground fault may imply a failure of the inverter, or it may imply a failure of a module or failure of wiring somewhere in the field. Identifying the location of the ground fault can be time consuming; identification may be aided by appropriate diagnostics, and development of techniques is ongoing.

It may be noted that DC arcs are more difficult to extinguish than AC arcs, for which the current drops to zero 120 times per second. The following are examples of causes of arcing that have been reported to lead to fires, and thus should be scrutinized when inspecting a system:

- **Abrasion of the insulation of a wire.** This issue could occur if a wire is dangling and blows in the wind or if a wire runs through a metal conduit and rubs against a burr inside of the conduit, especially with thermal expansion and contraction. All metal conduit should have the joints deburred after cutting and should be designed with thermal-cycle stress relief.

- **Module arcing.** A module that has inadequate electrical resistance between the active circuit and the grounded frame or nearby metal surface, including cracked modules, can cause arcing to occur.

- **Disconnect inside module.** If a connector inside a module breaks, it can stop the flow of current. Today's modules are designed to have redundancy in the busbar design so that if one busbar breaks, the current may flow through an adjacent one. The module includes bypass diodes to conduct the current when the path of the current might be otherwise interrupted.

More complete statistics about the causes of fires associated with solar systems can be found in Namikawa (2017).

5.3 Strategies for Addressing Faults

5.3.1 O&M Contracts

Contracts for O&M of solar systems have been decreasing in cost. The cost will be highly dependent on the size of the system, but prices below $10/kW/year may now be obtained for large systems within easy driving distance from the O&M provider's base of operation. New systems may benefit from O&M contracts that will enable problems to be identified during the initial year or two of operation. Installation contractors that provide O&M on the systems that they have installed will benefit from seeing problems that develop, enabling them to improve their installation practices. This is especially important as new hardware and installation processes are developed.

As mentioned above, if the installation contractor provides the O&M, the installation contractor can address warranty claims with minimal intervention from Caltrans, thereby avoiding the need for Caltrans to identify whether the installation contractor or the component manufacturer should be held responsible for a failure. Thus, O&M contracts may be most useful to Caltrans when:

- A relatively low price can be negotiated for the contract because the system is large, and the O&M provider is already providing service for multiple systems in the area.
- A system is new, and the installation contractor offers a service contract as a small extension of the installation contract and agrees to handle any needed warranty claims with component manufacturers.
- Experience with the installation contractor is limited and/or the system design is new and may experience new types of failures.
- The system is large enough that it benefits from specialized surveillance equipment. For example, the fastest way to inspect a 1-MW system is to have an airplane or drone fly over it rather than have an individual walk around and inspect every module.

5.3.2 In-House O&M

In-house O&M may be more cost effective for Caltrans when Caltrans can combine inspections of solar systems with other activities in the vicinity of the solar system, and if Caltrans has staff available with sufficient technical expertise. In particular, small systems that are easily accessed may be inspected in a short amount of time at minimal cost. Mowing operations along the right-of-way may be cost-effectively combined with vegetation control in the solar system, depending on the climate and vegetation control plan. In such a case, Caltrans personnel should be trained on the hazards of entering the site and, particularly, the possibility of damage to the solar system—for example, if a rock is thrown by a mower. In-house O&M may be beneficial when:

- The systems are routinely accessed by Caltrans personnel for other purposes.
- Access by an outside O&M company would require a Caltrans escort, causing inefficiency.

- The solar system is small enough that it can be inspected in a short time without the need for very expensive equipment.
- Caltrans has adequate in-house expertise to support solar generation facilities.
- Many identical systems are being serviced so that the supply of spare parts can be minimized while still enabling rapid repair of systems.

Caltrans may find it advantageous to contract for unplanned maintenance services but to provide vegetation control, cleaning, and inspections for nests and debris as well as routine inverter reboots in house. These latter activities can be accomplished without sophisticated knowledge and equipment. Unplanned maintenance may benefit from more specialized equipment (e.g., to measure module performance) and expertise (e.g., to identify the cause of a ground fault). Additionally, if Caltrans would need to maintain spare parts (as described next) for multiple differing systems, the service contract with a company that is maintaining spare parts for a large number of systems may turn out to be more cost effective. For example, an installation contractor is typically installing many systems using similar types of modules and inverters. If the company offers ongoing service for those systems, the company is likely to retain some of the original modules and inverters as spare parts.

5.4 Spares and Other Strategies to Aid in Maintenance

It is a best practice to maintain a supply of any spare parts that are found to need frequent replacement. This supply should be established at the time of system construction. Alternatively, if the system contract includes a service contract for the first couple of years, the supply may be established at the end of the service contract, using the repairs that were needed during the service contract as a guide for the inventory of spare parts that should be included in the supply. Frequently used supplies include:

- Inverters when microinverters or string inverters are used and/or inverter parts for large inverters.
- Modules.
- Fuses.
- Mounting hardware.
- Batteries for any data loggers that require batteries.
- Cable ties, though it is preferable to select a type of cable tie that has a long life.

In particular, not all inverter problems are fixed with a simple restart. Inverter replacement or repair is one of the most common unplanned maintenance operations. Inverter repairs that take weeks or even months to implement have been especially problematic because of the associated loss in system performance. Establishment of a spare parts supply that includes either the components that are most likely to fail in large inverters or spare string inverters may enable rapid repair or replacement. Some companies have moved toward standardizing the inverters they use so that they only need to maintain spares of one type of inverter.

6 SOLAR PHOTOVOLTAIC TECHNOLOGY

A clear understanding of the design of solar cells benefits from having studied solid-state physics, providing a thorough understanding of semiconductor materials and devices. A complete description is outside of the scope of this document, but a thorough treatment can be found at https://www.pveducation.org.

6.1 How Solar Cells (PV Devices) Convert Light to Electricity

Solar cells are electronic devices that produce electricity from sunlight. They achieve this by exploiting the physical phenomenon called the PV effect. Edmond Becquerel first discovered the PV effect in 1839 by experimenting with an early-stage battery made with electrolytes and silver plates. He observed that when exposing the battery to direct sunlight, the voltage increased. We now understand that the PV effect converts the incoming light to electric power (voltage and current). While the PV effect was discovered in the 1800s and explained by Einstein in the early 1900s, practical solar cells were not fabricated out of silicon until the 1950s at Bell Labs.

Nonetheless, not all materials experience the photovoltaic effect. The most suitable materials are semiconductors, and silicon is the most widely used. The semiconductor material is chosen to have a bandgap (optical property) that is a good match to the energy of the light that is illuminating the cell, typically sunlight. Silicon is a good choice for solar cells because its bandgap is about 1.1 eV, which allows it to absorb much of the solar spectrum and achieve a sunlight-to-electricity conversion efficiency that is close to the highest achieved for any material.

The theoretical maximum efficiency that can be achieved for any material can be calculated by modeling the detailed balance (Shockley & Queisser 1961) of transfer of light between the solar cell and the sun. The maximum efficiency that can be achieved for a single material as a function of band gap is shown in Figure 6.1 for two spectra: the reference spectra most commonly used for light striking the outside of the earth's atmosphere (air mass [AM] 0) and striking the earth's surface on a clear day (AM1.5).

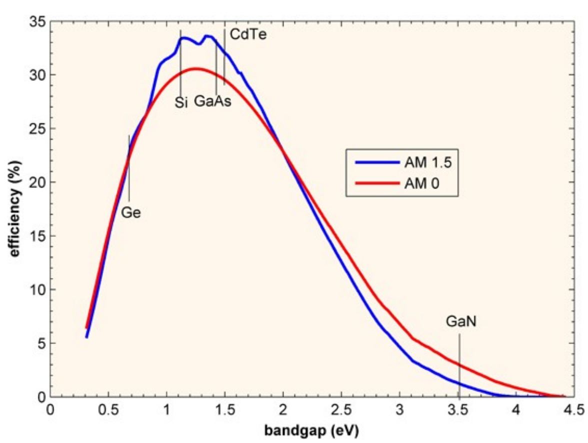


Figure 6.1. Theoretical maximum efficiency for solar cells as a function of bandgap.
Figure source: https://www.pveducation.org/pvcdrom/detailed-balance.

The silicon semiconductor material is a crystal (or many crystals) that can be made to have a range of electrical characteristics. This is done by adding elements (defects) to the crystal structure that have more or fewer electrons than the crystal has in its pure state. Silicon is a group IV element, so each silicon atom has four valence electrons. Adding elements with an additional electron per atom (group V atom) to the crystal structure creates an excess of electrons, resulting in an n-type material. Conversely, adding a group III atom causes a deficiency of electrons, called holes, resulting in a p-type material. In this way, solar cells are made to have an excess of electrons on one side of the cell (often the front) and an electron deficiency on the other side (often the back). This creates the sections of the solar cell labeled "N-type silicon" and "P-type silicon" in Figure 6.2. The n-type and p-type regions create an electric field called a junction that moves free electrons from one side of the device to the other, where they can be extracted.

Inside of the semiconductor, when the sunlight is absorbed, the photons excite the electrons, moving them from a low energy state (valence band) to a higher one (conduction band) and forming what are called free pairs of carriers (electrons and holes) that can move. If coupled with an external circuit, they can be extracted from the material producing an electrical current. The output current of the solar cell is DC. Figure 6.2 depicts a solar cell.

The front and back electrodes assist in carrying the current from the cells to the outside circuit. The anti-reflective coating increases the transmission of sunlight into the solar cell.

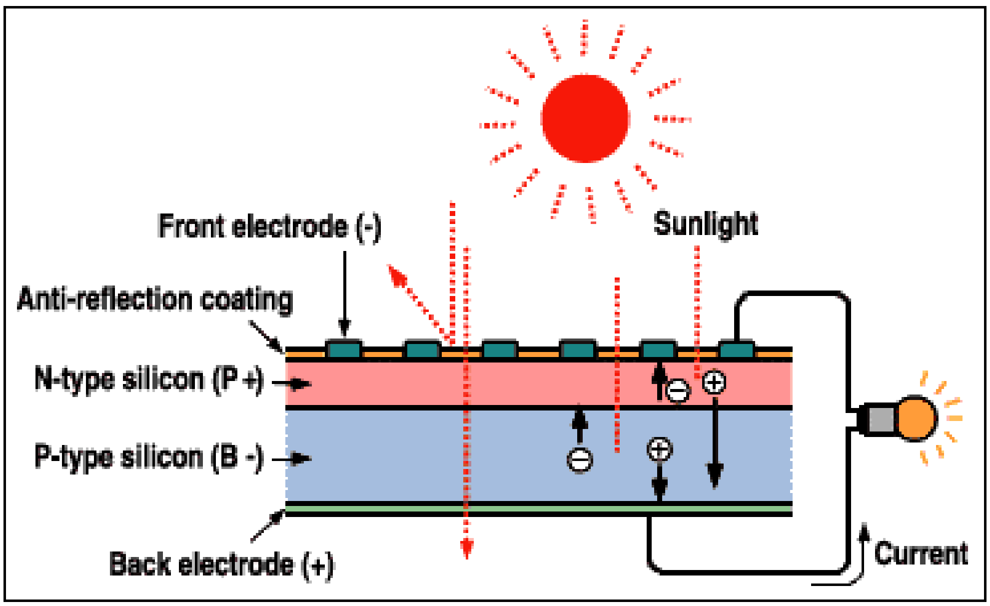


Figure 6.2. Schematic diagram of a typical solar cell. Figure source: https://chemistry.stackexchange.com/questions/113020/can-static-electricity-damage-solar-cells. Diagram was created by an unknown author and is licensed under CC BY-SA.

Solar cells can be made from many types of semiconductors. The historical record of champion solar cell efficiencies is shown in Figure 6.3. The chart documents more than a dozen types of solar cells. Within each of the traces, the exact materials and structures vary. Around 1995, the University of New South Wales developed a high-efficiency monocrystalline silicon cell with a passivated emitter that held the silicon efficiency record for many years. However, that structure was not commercialized for many years.

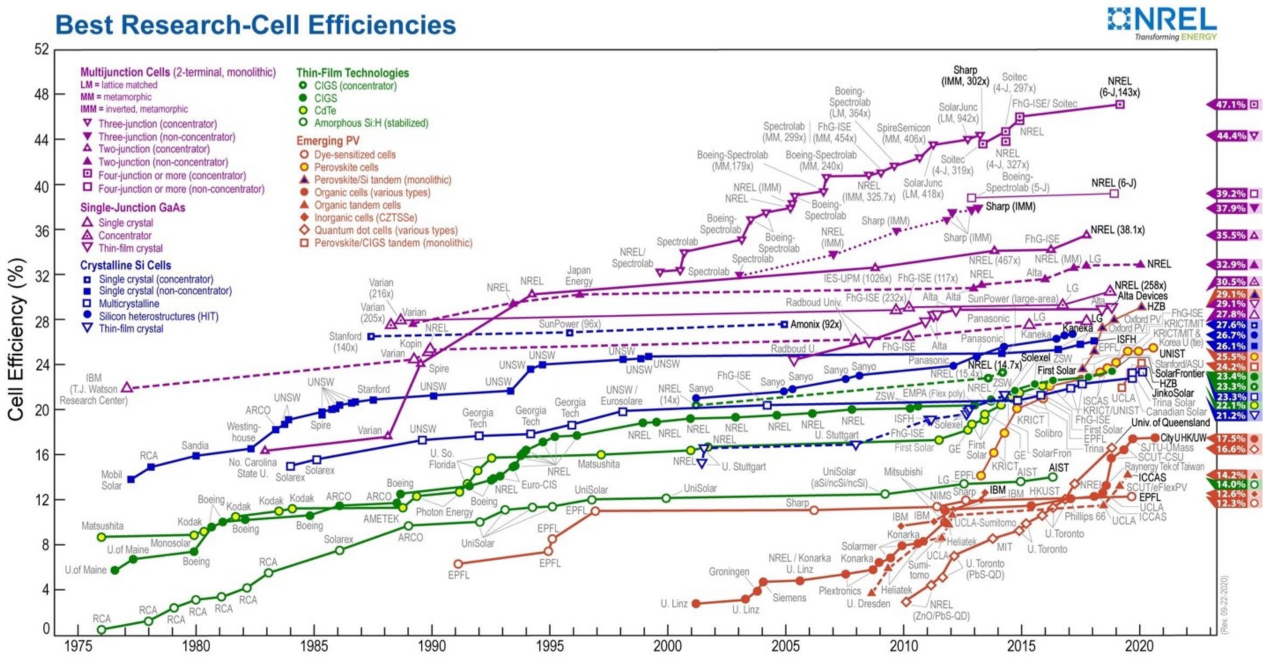


Figure 6.3. NREL champion solar cell efficiency chart. Figure source: https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.20200925.pdf.

The purification and refinement of silicon leading to the final solar cells can be done using many types of processes. The PV Education site provides an overview of Czochralski silicon growth (https://www.pveducation.org/pvcdrom/manufacturing-si-cells/czochralski-silicon) and flat zone silicon growth (https://www.pveducation.org/pvcdrom/manufacturing-si-cells/float-zone-silicon) as well as descriptions of many of the other processing steps (see pages following the above links).

Monocrystalline silicon has historically been grown for manufacturing as a large cylindrical ingot using the Czochralski method because the float-zone process was more expensive. By using a wire saw, the ingot is cut into thousands of slices called wafers. The round wafers are trimmed so that more cells can fit into a rectangular module. Thus, monocrystalline modules can often be easily recognized because the corners of the cells are slightly rounded—they may be referred to as pseudosquare. The record efficiency for monocrystalline silicon modules made using interdigitated back contact (IBC) solar cells is 24.4 percent (Green et al. 2019), meaning the module converts 24.4 percent of the sunlight's energy to electricity. A typical monocrystalline silicon 300-W solar module with a single series-connected string of 60 solar cells generates about 33 V and 9 amperes (A).

The other competing silicon technology is multicrystalline. The main difference between mono and multicrystalline is the growth process. The solar cells are made of fragments of silicon crystals that are melted together in a mold and then recrystallized before being cut into wafers. While monocrystalline silicon takes a longer time to grow in a perfect crystal structure, the multicrystalline is faster to produce and suffers fewer material losses because the wafer shape is naturally square. Currently, the most efficient multicrystalline silicon solar module is made by Hanwha Q-cells, with a 20.4 percent efficiency (Green et al. 2019).

6.2 Solar PV Systems

A solar PV system is composed mainly of an array of solar modules, mounting structures, inverters, wiring, and safety devices. A system can vary greatly in size depending on the application, from one-module systems providing stand-alone power to small rooftop configurations (typically 5 kW) to utility-scale (1 MW to 100 MW) plants. The electricity generated by the solar modules can be used directly, stored or fed into the grid. This section explains in further detail each component of the PV system.

The average solar installed residential system cost was $3–$4 per watt for the United States in 2019 (Feldman et al. 2019). A recent study of prices in five states (Arizona, California, Connecticut, Massachusetts, and New York) found the average system prices shown in Table 6.1, tabulated in $\$/W_{DC}$ which uses the power rating of the modules rather than of the inverters. This total includes the PV modules, inverters, structural and electrical components, and other costs such as installation labor, land acquisition, and sales tax.

Table 6.1. Recent System Prices in Five States (Feldman & Margolis 2020).

System size range	2017	2018	2019	First half 2020
2.5–10 kW	$\$4.3/W_{DC}$	$\$4.2/W_{DC}$	$\$4.1/W_{DC}$	$\$4.1/W_{DC}$
10–100 kW	$\$3.7/W_{DC}$	$\$3.6/W_{DC}$	$\$3.5/W_{DC}$	$\$3.6/W_{DC}$
100–500 kW	$\$2.8/W_{DC}$	$\$2.8/W_{DC}$	$\$2.6/W_{DC}$	$\$2.4/W_{DC}$
500 kW–5 MW	$\$2.3/W_{DC}$	$\$2.2/W_{DC}$	$\$2.0/W_{DC}$	$\$1.6/W_{DC}$

6.2.1 Solar Modules

The electric power produced by a single silicon solar cell is around 5 W. Multiple identical solar cells are interconnected in a series and encapsulated to form a solar module. The components of common solar modules are solar cells, encapsulant, front glass, backsheet, junction box (with cables), and metallic frame. The encapsulant retains the cells between the glass and the backsheet with the primary purpose of protecting the cells from the environment. Ethyl vinyl acetate is the most commonly used encapsulant material due to its low cost, transparency, and low thermal resistance. Most backsheets are made of polymeric materials, but glass is also being used. The function of the metallic frame, typically made from aluminum, is structural for mounting and handling. The frame structure should be free of projections that could result in the capture and retention of water, dust, or other matter. Finally, the junction box contains the electrical wiring and protection devices to extract the electricity out of the solar module. Figure 6.4 shows the schematic diagram of the main components of a solar module.

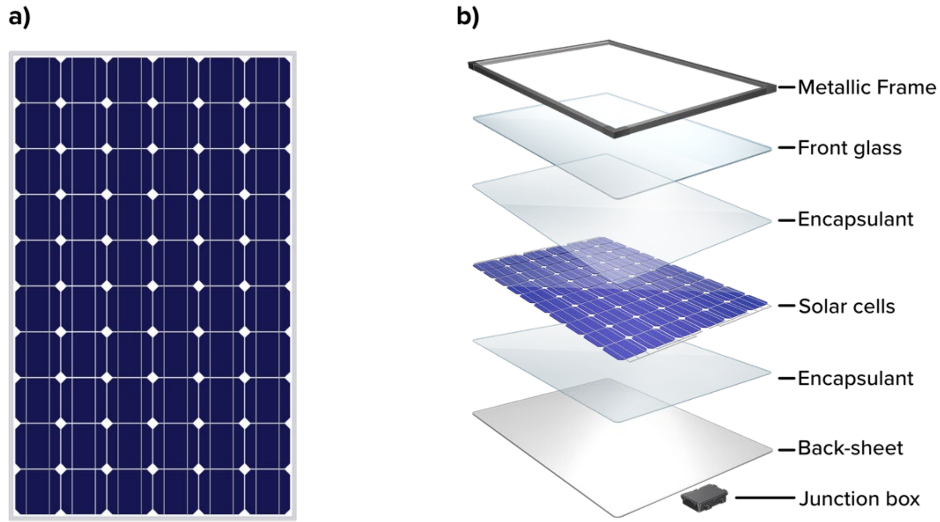


Figure 6.4. Silicon solar module structure: (a) silicon solar module, and (b) schematic diagram of the components of the solar module. Figure source: https://www.dupont.com/products/what-makes-up-a-solar-panel.html.

Over the years, many types of solar modules have been explored. The rapid progress of silicon modules has made it very difficult for other types of solar modules to compete. An example of an unusual product that was developed and deployed in California is Solyndra's copper indium gallium selenide (CIGS) modules fabricated in glass tubes and deployed in a very simple, lightweight structure, as shown in Figure 6.5. The tubes absorb light both arriving from the sky and reflecting off the reflective material placed under the tubes. Solyndra attracted substantial investment, including government funding, despite skepticism by mainstream solar experts. Solyndra's failure created much discussion about investment in high-risk technologies. Such modules are not manufactured today, but they demonstrate the breadth of possibilities for innovative concepts.

Figure 6.5. Deployed CIGS system by Solyndra. Photo credit: Kurtz.

Today, innovative research efforts are being focused on a hybrid organic-inorganic material based on lead iodide in a perovskite structure. As shown in Figure 6.3, the progress of these new cells has been spectacular. The commercialization of the different technologies may be tracked by the champion module efficiencies shown in Figure 6.6. This history and the basis of creating Figure 6.6 is described in a review article (Kurtz et al. 2018).

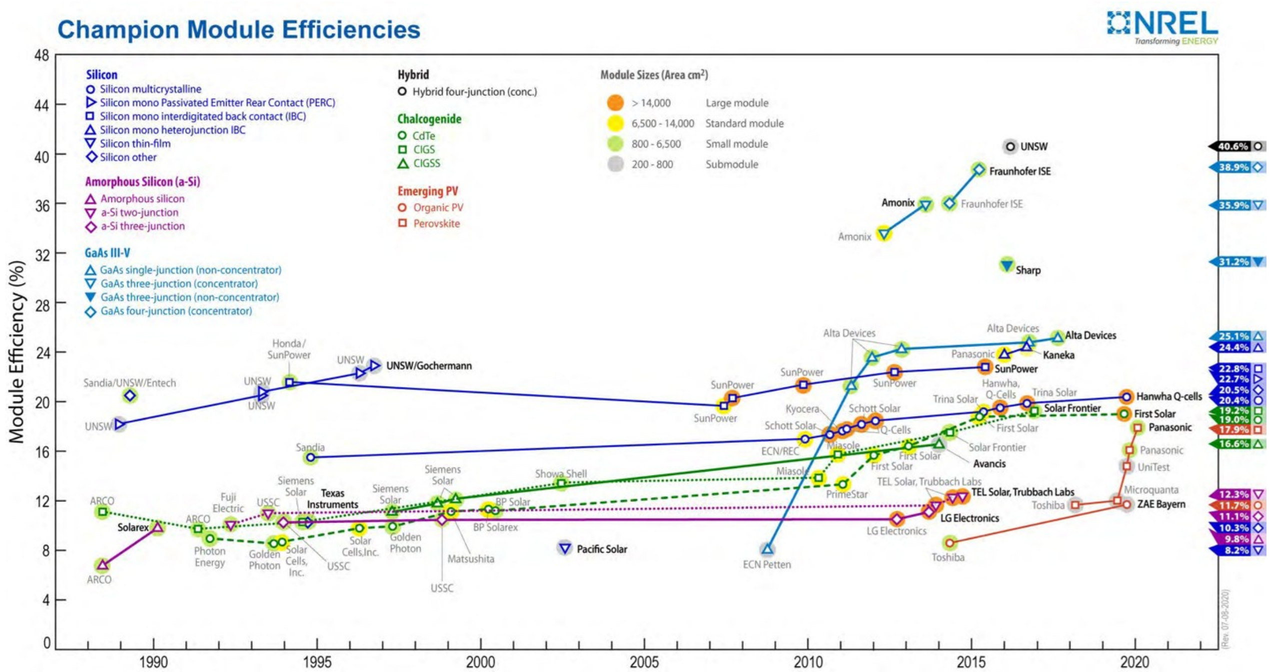


Figure 6.6. NREL champion solar module efficiency chart. Figure source: NREL (2020a).

6.2.1.1 Silicon Solar Modules

Silicon solar cells represent over 90 percent of the worldwide installed PV capacity (Ramanujam et al. 2020). Silicon technologies may be classified according to their crystal structure: monocrystalline and multicrystalline. Historically, there has been a competition between monocrystalline and multicrystalline solar cell manufacturers. Since both technologies wanted to increase their market share, they pushed their limits to reduce cost and increase cell efficiency. In the last decade or so, the lower cost of the multicrystalline modules has been more important than the higher efficiency of the monocrystalline modules, enabling multicrystalline modules to capture more than 50 percent of market share. In the last two years, the balance has shifted toward monocrystalline modules. Figure 6.7 shows examples of monocrystalline and multicrystalline silicon modules.

Figure 6.7. Typical commercial solar modules: a monocrystalline silicon solar (left); a multicrystalline silicon solar (right). The monocrystalline silicon solar module's distinctive pattern is a result of trimming the round ingot shape into an almost square (pseudosquare) shape with missing corners. Photo credit: Jorge Luis Carnalla Ortiz.

Both types of silicon solar modules can have different shapes or arrangements of cells depending on the applications. The most common are built with 60 cells, but some modules are made with a longer series-connected string of 72 cells or more. The 60-cell module is found in residential applications, while bigger modules are often used for large power plants.

The difference between monocrystalline and multicrystalline silicon modules is being blurred as more companies begin to use a process called "cast-mono."[5] The process is fairly similar to the multicrystalline casting process but results in wafers that are mostly monocrystalline, approaching the performance of monocrystalline at a multicrystalline cost.

The details of the cell structures can be highly variable. Examples of cells are shown in Figure 6.8 and Figure 6.9. Because each cell generates approximately 9 A of current (depending on the size of the cell), manufacturers optimize the design of the grid to carry that current with low series resistance, minimal shading of the cell, minimal cost, and high reliability. The grid style shown in Figure 6.8 is highly unusual but reflects the general trend toward smaller, closely spaced grid lines. It has been found that these apply less stress to the cell since the stress may be concentrated near the metal-semiconductor junction when the temperature changes and the very different materials expand or contract at different rates. In contrast, the cell shown in Figure 6.9 has no visible grid lines because both contacts are made to the back of the solar cell. In both Figure 6.8 and Figure 6.9, the cut corners suggest that monocrystalline wafers were used. The white backsheet helps to maximize performance relative to a module that is made to be all black because the white surface reflects light that may be guided back to the adjacent solar cell. However, an all-black module is thought to have a more pleasing appearance and is often marketed for residential applications. In Figure 6.9, the reflection of the cell phone and hand holding the cell phone can be seen as an artifact. Some dust is also visible.

[5] See, for example, https://www.youtube.com/watch?v=EZQtJU0Ib9Q.

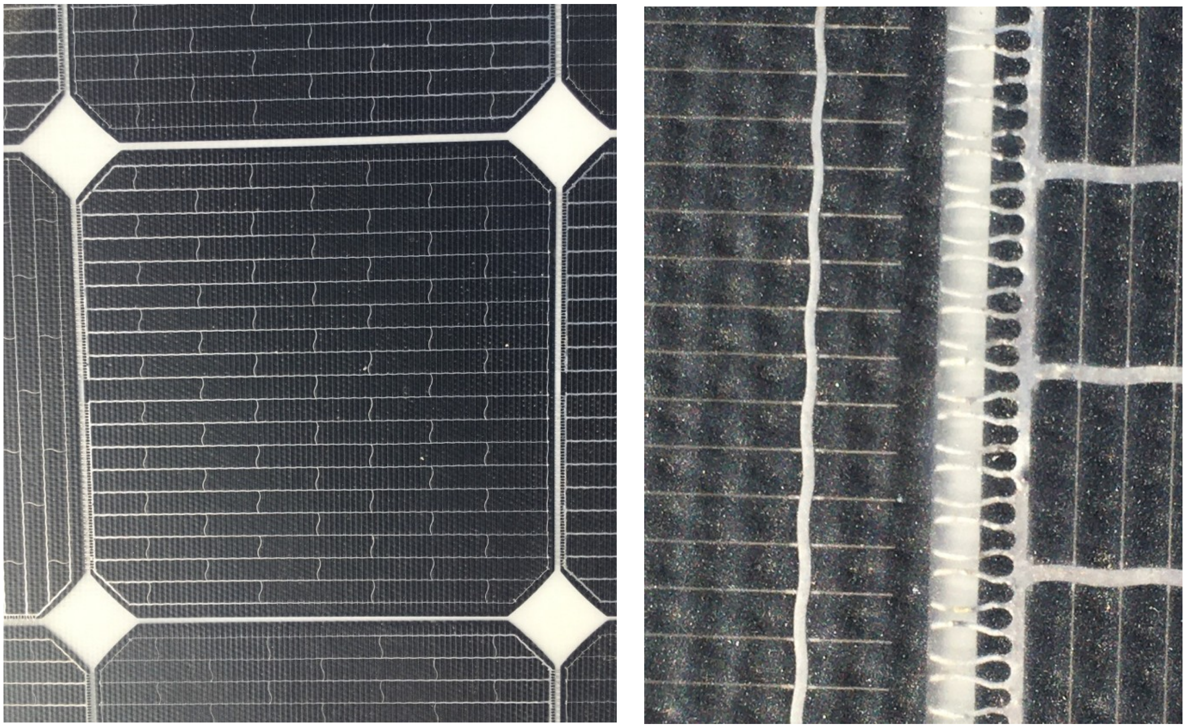


Figure 6.8. Photo of silicon cell with unusual grid pattern (left); enlarged image showing the interconnection of two cells (right).

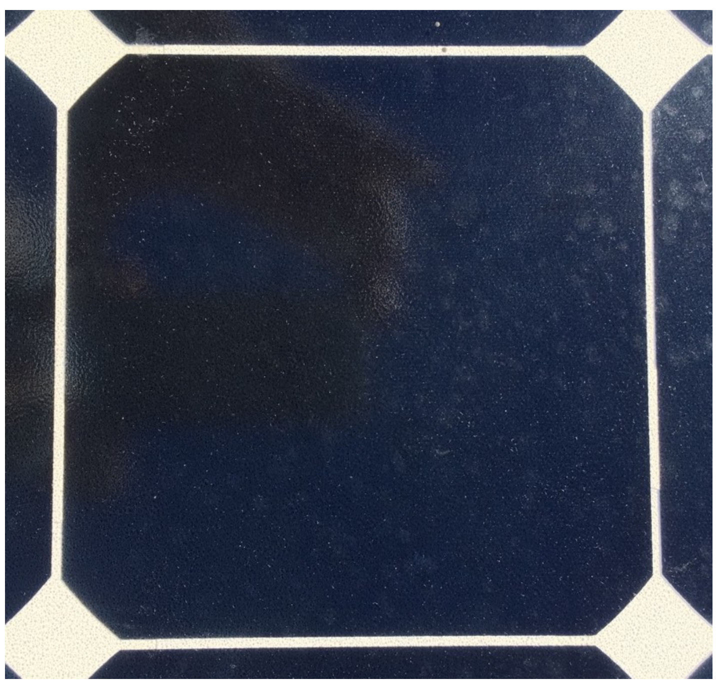


Figure 6.9. Image of cell in SunPower Module with no front grid pattern.

6.2.1.2 Thin-Film Solar Modules

Thin-film solar modules are made from a variety of materials. Today's commercialized thin-film technologies are cadmium telluride (CdTe) and CIGS.[6] Thin-film solar modules use solar cells that are typically 1 µm to 5 µm thick, while the solar cells in silicon modules use solar cells with thickness greater than 100 µm. About 5 percent of solar modules produced today are thin-film technologies (Fraunhofer Institute for Solar Energy Systems 2020).

The technology that dominates the thin-film market is CdTe. Its current market share is around 5 percent of the worldwide solar market (Fraunhofer 2020). In 2020, the company First Solar hit the record efficiency of 19 percent (Green et al. 2019) for CdTe. First Solar is the only mainstream manufacturer of CdTe modules. Most CdTe modules are made using close-spaced sublimation of the CdTe active layer. CdTe modules have a lower cost to manufacture and show better electrical performance for higher-temperature places like deserts (Strevel et al. 2012). A First Solar Series 6 CdTe module is specified to generate 450 W delivered with 187 V and 2.4 A. Other companies are developing CdTe modules for niche markets, including some decorative concepts, as shown in Figure 6.10.

(a) (b) (c)

Figure 6.10. Images of CdTe modules with tailored appearances: (a) module that is semitransparent to reduce glare but enable visibility of objects on other side (in this case, the pattern of the carpet can be seen), (b) module that appears to be a wood panel, and (c) module that appears to be a painting.
Photo credit: Kurtz.

CIGS is another type of thin-film solar module available today. The record efficiency for a CIGS module is currently 18.6 percent (Green et al. 2019). CIGS solar modules are manufactured by several different techniques including sputtering, chemical vapor transport, co-evaporation, and printing techniques, typically using molybdenum-on-glass as a substrate. Solar Frontier is currently the largest manufacturer of CIGS modules. Solar Frontier's 175-W CIGS solar module

[6] Amorphous silicon solar cells can be found powering some consumer products but are no longer commercialized for bulk power generation.

generates 90 V and 2 A. The main advantage of this technology is that it can be deposited onto different types of substrates—glass, plastic, and flexible materials—which makes it suitable for a variety of nontraditional applications (e.g., car rooftop, wings of airplanes, transportation, marine and solar façades), as shown in Figure 6.11. Unfortunately, the Chinese company (Hanergy) that purchased most of the U.S. CIGS companies recently closed all of the U.S. companies that were developing these unique products.

Figure 6.11. HANERGY backpack with semi-flexible CIGS solar module.

For reference, the technologies described in this section are summarized in Table 6.2.

Table 6.2. Commercial Solar Cell Technologies.

Cell Type	Module Record Efficiency	Market Share	Comments
Monocrystalline silicon	24.4%	>50%	Growing market share
Multicrystalline silicon	20.4%	<50%	Shrinking market share
CdTe	19%	~5%	Dominated by U.S. company First Solar
CIGS	16.1%	~1%	Dominated by Japanese company Solar Frontier

6.2.1.3 Emerging Technologies

As an alternative to silicon, CdTe, and CIGS solar modules, emerging PV technologies intended to have lower production cost or higher efficiency are currently in development. The technology currently attracting the largest attention uses hybrid organic-inorganic, lead-iodide-based perovskite solar cells. The structure of calcium titanium oxide is known as the "perovskite structure." Solar cells using lead halide perovskite as an absorbing layer, manufactured by an inkjet-base coating method, have shown a record initial efficiency of 16.1 percent for an 802 cm^2 module, and higher efficiencies are announced each year. This new technology still requires additional improvement to scale to large modules and demonstrate adequate stability and reliability.

Each year, tens of thousands of papers are published describing research to improve solar cell and solar module technologies. This best practices summary focuses on commercially available products. The final report will include a more complete description of solar technologies that may become important in the next 10 years.

6.2.1.4 Data Sheets and Other Sources of Information

The electrical parameters of a solar module depend on the technology, the number of solar cells connected in series or parallel, and the manufacturing reproducibility. When initiating the manufacturing process, a data sheet is created that spans the range of properties that are typically observed from that manufacturing process. An example data sheet for a SunPower module is shown in Figure 6.12 and Figure 6.13. This data sheet describes two versions of this module, with the 335-W version using a black backsheet to provide the uniformly black appearance and the 345-W version using a white backsheet.

SunPower® X-Series Residential Solar Panels | X21-335-BLK | X21-345

More than 21% Efficiency

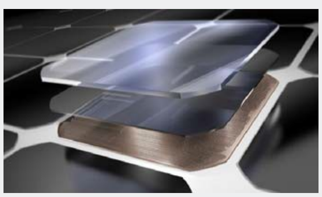
Ideal for roofs where space is at a premium or where future expansion might be needed.

Maximum Performance

Designed to deliver the most energy in demanding real-world conditions, in partial shade and hot rooftop temperatures.[1,2,4]

Premium Aesthetics

SunPower® Signature™ Black X-Series panels blend harmoniously into your roof. The most elegant choice for your home.



Maxeon® Solar Cells: Fundamentally better
Engineered for performance, designed for durability.

Engineered for Peace of Mind

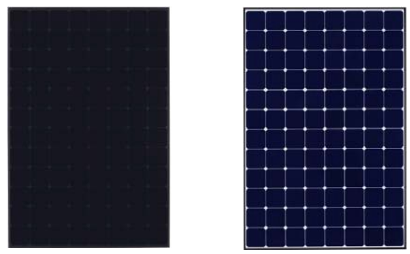
Designed to deliver consistent, trouble-free energy over a very long lifetime.[3,4]

Designed for Durability

The SunPower Maxeon Solar Cell is the only cell built on a solid copper foundation. Virtually impervious to the corrosion and cracking that degrade conventional panels.[3]

Same excellent durability as E-Series panels.
#1 Rank in Fraunhofer durability test.[9]
100% power maintained in Atlas 25+ comprehensive durability test.[10]

Unmatched Performance, Reliability & Aesthetics



X21 SERIES

SIGNATURE™ BLACK SPR-X21-335-BLK | SPR-X21-345

Highest Efficiency[5]

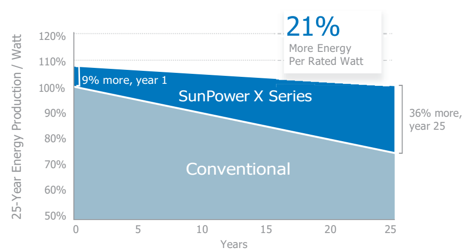
Generate more energy per square foot

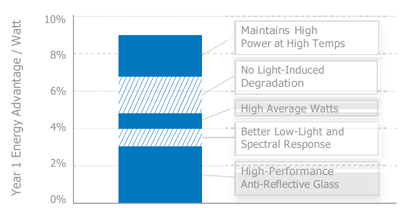
X-Series residential panels convert more sunlight to electricity by producing 38% more power per panel[1] and 70% more energy per square foot over 25 years.[1,2,3]

Highest Energy Production[6]

Produce more energy per rated watt

High year-one performance delivers 8–10% more energy per rated watt.[2] This advantage increases over time, producing 21% more energy over the first 25 years to meet your needs.[3]





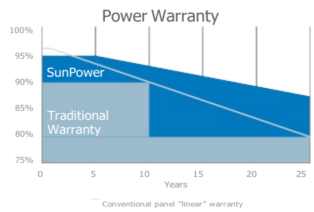
Datasheet

SUNPOWER®

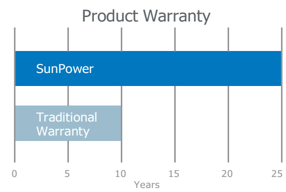
Figure 6.12. Data sheet for SunPower X-Series modules. Source: https://us.sunpower.com/sites/default/files/media-library/data-sheets/ds-x21-series-335-345-residential-solar-panels.pdf, page 1.

SunPower® X Series Residential Solar Panels | X21-335-BLK | X21-345

SunPower Offers The Best Combined Power And Product Warranty



More guaranteed power: 95% for first 5 years, –0.4%/yr. to year 25 [7]



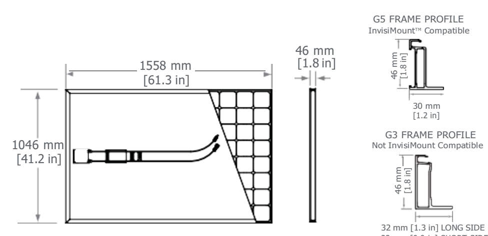
Combined Power and Product defect 25-year coverage [8]

Electrical Data	SPR-X21-335-BLK	SPR-X21-345
Nominal Power (Pnom)[11]	335 W	345 W
Power Tolerance	+5/–0%	+5/–0%
Avg. Panel Efficiency[12]	21.0%	21.5%
Rated Voltage (Vmpp)	57.3 V	57.3 V
Rated Current (Impp)	5.85 A	6.02 A
Open-Circuit Voltage (Voc)	67.9 V	68.2 V
Short-Circuit Current (Isc)	6.23 A	6.39 A
Max. System Voltage	600 V UL & 1000 V IEC	
Maximum Series Fuse	15 A	
Power Temp Coef.	–0.29% / °C	
Voltage Temp Coef.	–167.4 mV / °C	
Current Temp Coef.	2.9 mA / °C	

REFERENCES:
1 All comparisons are SPR-X21-345 vs. a representative conventional panel: 250 W, approx. 1.6 m², 15.3% efficiency.
2 Typically 8–10% more energy per watt, BEW/DNV Engineering "SunPower Yield Report," Jan 2013.
3 SunPower 0.25%/yr degradation vs. 1.0%/yr conv. panel. Campeau, Z. et al. "SunPower Module Degradation Rate," SunPower white paper, Feb 2013; Jordan, Dirk "SunPower Test Report," NREL, Q1-2015.
4 "SunPower Module 40-Year Useful Life" SunPower white paper, May 2015. Useful life is 99 out of 100 panels operating at more than 70% of rated power.
5 Highest of over 3,200 silicon solar panels, Photon Module Survey, Feb 2014.
6 1% more energy than E-Series panels, 8% more energy than the average of the top 10 panel companies tested in 2012 (151 panels, 102 companies), Photon International, Feb 2013.
7 Compared with the top 15 manufacturers. SunPower Warranty Review, May 2015.
8 Some restrictions and exclusions may apply. See warranty for details.
9 X-Series same as E-Series, 5 of top 8 panel manufacturers tested in 2013 report, 3 additional panels in 2014. Ferrara, C., et al. "Fraunhofer PV Durability Initiative for Solar Modules: Part 2". Photovoltaics International, 2014.
10 Compared with the non-stress-tested control panel. X-Series same as E-Series, tested in Atlas 25+ Durability test report, Feb 2013.
11 Standard Test Conditions (1000 W/m² irradiance, AM 1.5, 25° C). NREL calibration Standard: SOMS current, LACCS FF and Voltage.
12 Based on average of measured power values during production.
13 Type 2 fire rating per UL1703:2013, Class C fire rating per UL1703:2002.
14 See salesperson for details.

Tests And Certifications	
Standard Tests[13]	UL1703 (Type 2 Fire Rating), IEC 61215, IEC 61730
Quality Certs	ISO 9001:2008, ISO 14001:2004
EHS Compliance	RoHS, OHSAS 18001:2007, lead free, REACH SVHC-163, PV Cycle
Sustainability	Cradle to Cradle Certified™ Silver (eligible for LEED points)[14]
Ammonia Test	IEC 62716
Desert Test	10.1109/PVSC.2013.6744437
Salt Spray Test	IEC 61701 (maximum severity)
PID Test	Potential-Induced Degradation free: 1000 V[9]
Available Listings	UL, TUV, JET, MCS, CSA, FSEC, CEC

Operating Condition And Mechanical Data	
Temperature	–40° F to +185° F (–40° C to +85° C)
Impact Resistance	1 inch (25 mm) diameter hail at 52 mph (23 m/s)
Appearance	Class A+
Solar Cells	96 Monocrystalline Maxeon Gen III
Tempered Glass	High-transmission tempered anti-reflective
Junction Box	IP-65, MC4 compatible
Weight	41 lbs (18.6 kg)
Max. Load	G5 Frame: Wind: 62 psf, 3000 Pa front & back Snow: 125 psf, 6000 Pa front G3 Frame: Wind: 50 psf, 2400 Pa front & back Snow: 112 psf, 5400 Pa front
Frame	Class 1 black anodized (highest AAMA rating)



G5 frames have no mounting holes. Please read the safety and installation guide.

See www.sunpower.com/facts for more reference information.
For more details, see extended datasheet: www.sunpower.com/datasheets.

Document # 504828 Rev F /LTR_US

SUNPOWER®

Figure 6.13. Data sheet for SunPower X-Series modules. Source: https://us.sunpower.com/sites/default/files/media-library/data-sheets/ds-x21-series-335-345-residential-solar-panels.pdf, page 2.

The data sheet shown in Figure 6.12 and Figure 6.13 may be compared to the nameplate label shown in Figure 6.14. The rated power is 345 W (+5/−0 percent), indicating that the module when measured under standard test conditions will be found to have a power between 345 W and 362 W. In practice, the measured power may fall outside of that range, reflecting the uncertainty of the measurement. The measurement that provides the 345-W rating is associated with a voltage and a current. In this case, the voltage (labeled as Vmp) is 57.3 V and the current (labeled as Imp) is 6.02 A, the product of which is 345 W. This SunPower module uses smaller cells than some other products, but SunPower's recent reorganization included a plan to begin using larger cells, which will result in lower costs but higher current ratings that are closer to what other products are reported to provide. The open-circuit voltage and short-circuit current are also listed on the data sheet. The maximum fuse to use is 15 A, enabling currents higher than the rated 6.4 A, which may be observed during cloud-brightening events (when light reflects from a nearby cloud to supplement the sunlight that is already striking the module directly). The nameplate also indicates a number of relevant safety warnings and indicates the certifications that the product maintains.

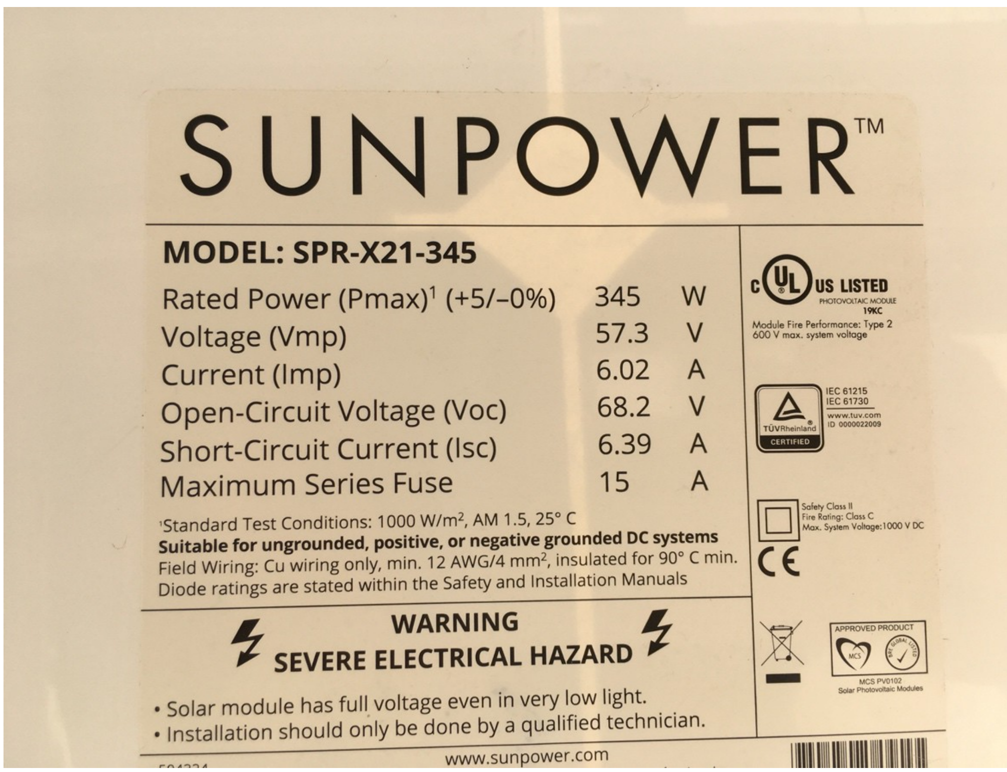


Figure 6.14. Nameplate label for module described in Figure 6.12 and 6.13.

The information on the nameplate is also found on the data sheet of the model. Electrical parameters are typically measured at standard testing conditions (STC) that correspond to 1,000 W/m², AM1.5 clear-day spectrum, and 25°C cell temperature. Performance at nominal module operating temperature measured at 800 W/m², AM1.5, 20°C air temperature, 1 m/s wind speed may also be reported. Modules actually operate outdoors under all types of conditions, so the user must be able to translate using the measurements provided at STC plus temperature coefficients and spectral response to model performance under any set of conditions.

The nameplate affixed to the solar module documents the following:

- Rated nominal power (P_{max}).
- Rated nominal short-circuit current (I_{sc}).
- Rated open-circuit voltage (V_{oc}).
- Name and logo of original manufacturer and model number.
- Serial number or information about location and date of manufacture.
- Electrical shock protection class.
- Maximum system voltage allowed.
- Production tolerance (− % and + %) of P_{max} at STC.

Temperature coefficients for the performance can sometimes be found on the nameplate and should always be included in the data sheet. These coefficients indicate the electrical performance of the solar module when operating at different temperatures. Temperature coefficients are usually expressed as a percentage change per degree of temperature and are of great value for estimating the performance of the solar module under operating conditions. The module operating temperature varies with ambient temperature, the sun's heating of the module, and wind speed.

The data sheet also includes the mechanical specifications of the unit. Typically, this information includes the dimensions, weight, and recommended points to fix the metallic frame. This information is relevant for the solar installation contractors to conduct an appropriate equipment selection so as to ensure a long-lasting installation. For additional information, the California Energy Commission (CEC) has a compilation of different commercial solar modules with the technical specifications included in the data sheet (CEC 2020).

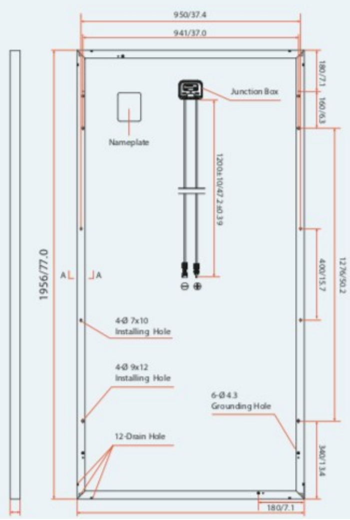
A section of the data sheet for Trina's TALLMAX framed 72-cell module is shown in Figure 6.15. This data sheet provides specifications for modules that may be rated as 320 W, 325 W, 330 W, or 335 W. In this case, the power output tolerance is 0 to +5 W. The module is viewed to be nominally the same product (TALLMAX) regardless of which W rating is assigned. The manufacturer measures the properties of every module coming from the production line and places each in a bin that corresponds to its properties. In the case of the TALLMAX product, the first bin is used for 320-W to 325-W modules, and so on. The appropriate nameplate tag is affixed—typically to the back of the module—to show the electrical parameters associated with that bin and also provides a serial number, which should be traceable back to the components that were used to manufacture the module in case a problem is identified with one of the components later.

TALLMAX

FRAMED 72-CELL MODULE

PRODUCTS	POWER RANGE
TSM-PD14	320-335W

DIMENSIONS OF PV MODULE (mm/inch)



ELECTRICAL DATA (STC)

Peak Power Watts-P_{MAX} (Wp)*	320	325	330	335
Power Output Tolerance-P_{MAX} (W)	0 ~ +5			
Maximum Power Voltage-V_{MPP} (V)	37.1	37.2	37.3	37.6
Maximum Power Current-I_{MPP} (A)	8.63	8.76	8.87	8.91
Open Circuit Voltage-V_{OC} (V)	45.8	45.9	46.1	46.3
Short Circuit Current-I_{SC} (A)	9.10	9.25	9.38	9.39
Module Efficiency η_m (%)	16.5	16.8	17.0	17.3

STC: Irradiance 1000W/m², Cell Temperature 25°C, Air Mass AM1.5.
*Measuring tolerance: ±3%.

ELECTRICAL DATA (NOCT)

Maximum Power-P_{MAX} (Wp)	238	242	246	249
Maximum Power Voltage-V_{MPP} (V)	34.4	34.5	34.6	34.9
Maximum Power Current-I_{MPP} (A)	6.91	7.02	7.11	7.14
Open Circuit Voltage-V_{OC} (V)	42.5	42.6	42.7	42.9
Short Circuit Current-I_{SC} (A)	7.35	7.47	7.57	7.58

NOCT: Irradiance at 800W/m², Ambient Temperature 20°C, Wind Speed 1m/s.

Figure 6.15. Section of data sheet for Trina's TALLMAX framed 72-cell module.
Source: http://static.trinasolar.com/sites/default/files/PS-M-0328%20E%20Datasheet_Tallmax_US_Feb_2017_A.pdf.

6.2.1.5 Quality and Reliability Considerations

Once installed, the solar modules will be exposed to environmental factors such as temperature, humidity, rain, ultraviolet (UV) irradiation, thermal stress, and other mechanical stresses. Failures of modules in the field have been studied, and accelerated stress tests have been devised to quickly identify designs that will experience these failures. These tests have been standardized and have had great success in identifying designs that will function well in the field. The main objective of the design qualification is to represent the performance capability under prolonged exposure to standard climates. IEC published a set of standards, which are discussed in Appendix B. The IEC 61215 series of standards provides a set of accelerated stress tests used to qualify PV modules for use in most terrestrial environments.

Solar modules can also pose a potential risk of electric shock if improperly constructed. For this reason, it is necessary that they meet mandated safety requirements. IEC 61730 and UL 61730 (formerly UL1703) standards address the safety aspects of a solar module, covering both an assessment of module construction and test requirements to assess thermal, electrical, mechanical, and fire safety.

The data sheet and the nameplate of the module have information about the conformity assessment, specifically the safety, performance evaluation, and design qualification standards that they have conformed to. It is important to verify that information because the modules that meet these standards are more likely to be reliable, durable, and safe; thus, it is always recommended to use modules that are qualified to the appropriate performance and safety standards. For additional information, CEC provides a database with the commercial solar modules that hold certification and which certification they have (CEC 2020).

6.2.2 *Mounting of Modules*

Common mounting configurations are summarized in Table 6.3. These configurations are then discussed following the table.

Table 6.3. Mounting Configurations.

Mounting Configuration	Description	Common Usage	Advantages	Disadvantages
Fixed	The modules are mounted on a stationary surface and do not move.	Residential, roof-mounted, and small systems	Is usually lower in cost	Usually generates less electricity
Single-axis tracked	The modules rotate around one axis. Most commonly, the axis lies north-south in the horizontal plane.	Utility-scale installations	Optimizes power out relative to cost for most large systems, especially in sunny areas	Tracking may add costs with minimal benefit in cloudy areas
Dual-axis tracked	The modules are rotated to be perpendicular to the direct beam from the sun at all times.	Not commonly used	Has highest output possible by always facing the sun directly	Adds cost; to avoid shading losses, the modules must be spaced well apart
Ground-mounted	The modules are mounted on supports that are connected directly to the ground.	Utility-scale and other applications with substantial space	Is often easier to mount directly on the ground if the land is available	Requires land
Structure-mounted	The modules are mounted on a building or other structure.	Residential or commercial applications	Often enables generation of electricity in the location where it is needed	Mounting on a roof can easily cause leakages and other problems

6.2.2.1 Hardware Requirements

In contrast with wind technology, solar systems using fixed mounting do not have any moving parts during electricity generation. These fixed PV systems are installed on a stable surface to provide protection for the module and to ensure that modules are secure in high wind conditions. The PV modules are attached to a structure that is referred to as the mounting system. It is often made of anodized aluminum because it is a lightweight material compared to steel and resists corrosion. Mounting structures may also be made of galvanized steel or other construction materials. Depending on the application, there are two categories for mounting systems: rooftop and ground-mount systems. To comply with local and international standards, the structure should be able to withstand hail, snow, and wind loads.

Roof-mounted systems have a metallic rack placed parallel to the roof, if pitched, or may be attached by ballast (weight that prevents the modules from blowing away) for a flat roof. South-facing latitude tilt provides more electricity generation on an annual basis. On flat roofs, the modules are typically mounted at 10-degree to 15-degree tilt to reduce wind loading and the associated need for robust mounting. The weight of the mounting system (including ballast) may exceed the rated load for the roof, so use of lightweight mounting hardware is helpful.

The ground-mounted configuration is more common in medium to large-scale applications. These types of systems can be further classified as fixed-tilt or tracking systems. Fixed-tilt systems have the modules set at a particular angle, which is often the same as the site's latitude. One main advantage of fixed-tilt mounting is lower operational and maintenance costs as well as lower initial cost for the structure.

Tracking systems usually use linear actuators to align the modules so they follow the sun's path. These mounting systems are classified depending on the number of axes that rotate: one axis and two axes. One-axis tracking is quite common today; two-axis tracking is quite uncommon because of the added cost and relatively small performance boost over single-axis tracking. Both types of tracking systems align the modules so they follow the sun's trajectory and keep them perpendicular to the solar rays in the tracked orientation(s) to maximize the insolation. The primary advantage of using tracking systems is the increase in energy yield over fixed tilt. For a single-axis tracking system, the energy yield increases up to 25 percent, while for a dual-axis system, it can be up to 35 percent (Kiatreungwattana et al. 2016; Hafez et al. 2018). However, having moving parts increases the operation and maintenance cost as well as the installation cost. Failure of a tracking system results in lost energy collection. Tracking should only be used where systems will be maintained to minimize such losses.

Depending on site conditions, the use of a tracking system usually enables a higher yield of electricity on an annual basis. However, if the site has a poor solar resource, the tracking system may not represent a performance advantage over fixed tilt. It is important to simulate energy production considering the mounting cost in order to estimate the optimal trade-off between the mounting cost and energy output.

6.2.2.2 Orientation and Non-solar Resource Considerations

The PV system needs to be oriented to maximize the yield of electricity, especially at the time of year and time of day when the electricity is needed. Typically, this is done by changing the orientation of the installation. For sites located in the northern hemisphere, fixed systems are usually oriented south facing and at latitude tilt. North-facing mounting will result in lower electrical yields. The south-facing, latitude-tilt conditions provide the maximum amount of energy yield on an annual basis. However, the tilt can be adjusted to maximize the yield at a specific time of the year, as shown in Figure 6.16.

For maximum generation in winter (days 0–50 and 300–350 in Figure 6.16), the tilt is set to be the latitude of the location +15 degrees to match when the sun transits the celestial meridian at a low angle. Conversely, selecting a horizontal or latitude −15-degree orientation will increase output in summer when the sun is higher in the sky (as shown for days 100–230 in Figure 6.16).

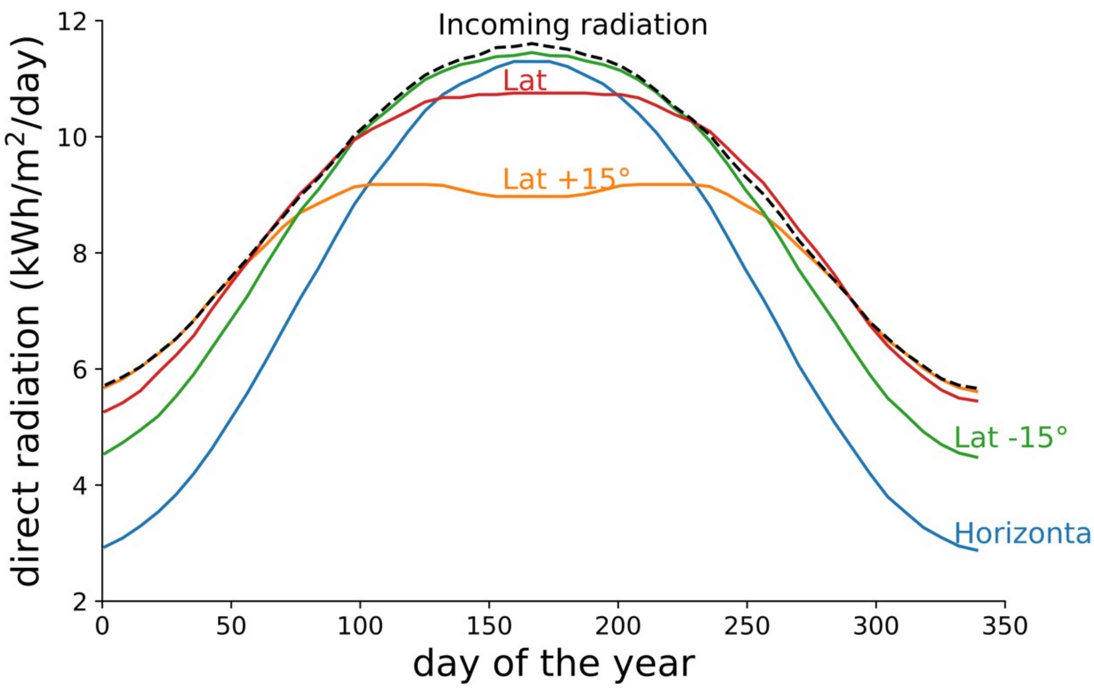


Figure 6.16. Simulation of daily insolation. Simulation of the daily insolation over a whole year for surfaces tilted toward the south by the latitude (37 degrees), latitude plus 15 degrees (aimed more to the south to better catch the winter sun), and latitude minus 15 degrees (closer to horizontal to better catch the summer sun).

In places where energy consumption increases late in the day, which is a typical pattern of people returning home from work and using more electricity, it is more beneficial to face the solar panels slightly southwest to maximize generation during the peak hours of consumption. The solar output expected for a south-facing system (solid blue line) is compared with the output of a west-facing system (dashed blue line) in Figure 6.17. The PVWatts simulation was done for a day in July for one location, showing the output of a 40-GW (over-scaled for direct comparison) fixed PV system with 20-degree tilt south facing and 20-degree tilt west facing. The output is compared with the actual California Independent System Operator (CAISO)-reported load for July 29, 2020, and with the CAISO-reported solar output for the same day. Note that the shapes of the two profiles are substantially different, mostly because the majority of the solar data reported by CAISO is from utility-scale systems with large DC-AC ratios, resulting in substantial clipping, and because the data reflect solar output across California, with the sun rising and setting at a variety of times.

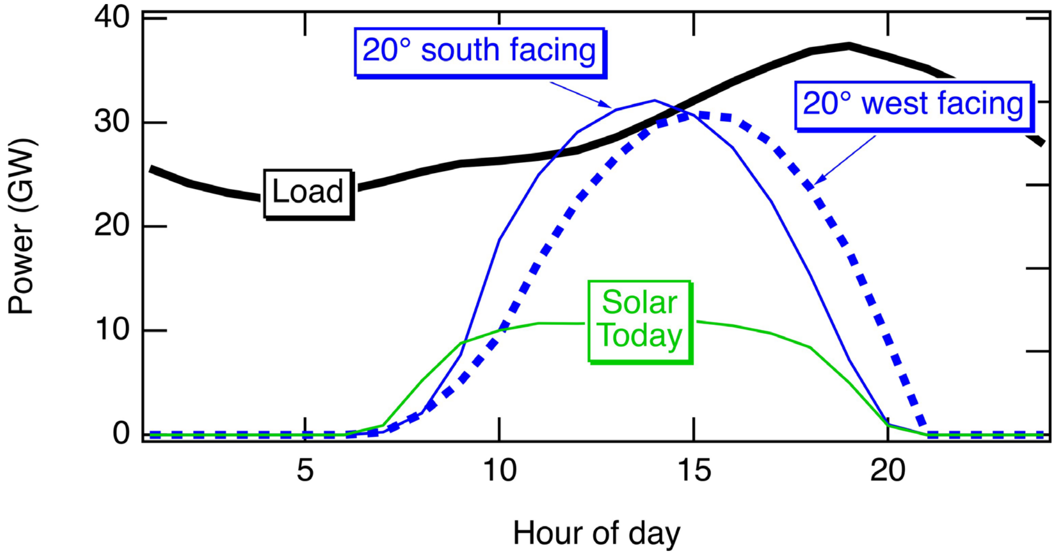


Figure 6.17. Simulation of hourly system output compared with California electrical load.

6.2.3 *Inverters*

Inverters are a critical component of PV systems because they are the bridge between the PV system and the electrical grid. Inverters by themselves do not produce any power but convert the DC electricity from the solar array into AC electricity for end use. Inverters must synchronize the PV electricity to a given frequency (60 Hz for the United States) and have shallow harmonic signals according to the utility requirements to maintain the stability of the electrical grid. Also, most of the inverters include maximum-power-point tracking to adjust the electrical bias so as to obtain the maximum power from the PV array (Solarpraxis AG 2011). An example of how the power varies with voltage bias is shown in Figure 6.2. Inverters use many different approaches for identifying the optimal bias.

6.2.3.1 Sizing of Inverters

An inverter is selected to match the PV array in two key metrics:

- The desired AC output power, with characteristics consistent with grid connection (frequency and voltage, which may depend on the use of a transformer).
- The desired DC input voltage range (or window).

Matching of the first key metric is done by considering the DC-to-AC ratio, also called the inverter-loading ratio. The DC-to-AC ratio is the ratio between the PV array capacity (the sum of the power ratings for all of the modules sending electricity to the inverter being considered) to the AC power rating of the inverter connected to them. Historically, PV installations were built with a DC-to-AC ratio equal to 1 because modules were expensive, so the inverter was selected to be able to convert all of the electricity generated by the array. However, as module prices have decreased, the relative costs of the inverter, transformer, and transmission line have become more important, and selection of a larger DC-to-AC ratio then enables full usage of the AC connection a larger fraction of time. When the DC-to-AC ratio is equal to 1, the PV system produces partial generation most of the day and may reach peak generation at solar noon on a clear day. If the DC-to-AC ratio is higher than 1 or oversized, at solar noon, the inverter output may be limited by its power rating, and the excess electricity is wasted (clipping). However, this also increases the time that the PV system delivers its rated AC power—see Figure 6.18. Having a high DC-to-AC ratio is useful when a constant supply of power is desired and will require less expensive inverter and transformer equipment. Higher ratios are also especially advantageous when a higher power output would require installing a new transmission line. Today's DC-to-AC ratios are typically 1.2–1.4 (Sánchez-Pérez & Kurtz 2020b). As batteries are added to systems, there is discussion of increasing DC-to-AC ratios to > 2.

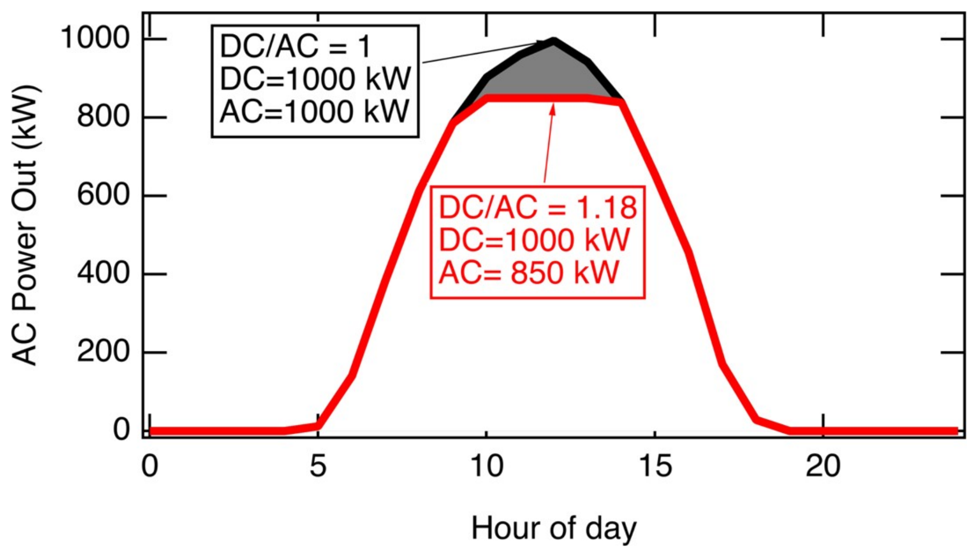


Figure 6.18. Output on a sunny day with and without clipping. Inverter AC output over the course of a day for a system with a DC-to-AC ratio = 1 (black curve, with part of curve hidden by the red curve) and DC-to-AC ratio = 1.18 (red curve). The gray area represents the energy that is lost to clipping, but such clipping does not occur every day, and the system with AC rating of 850 kW will be less expensive because of smaller inverter and smaller transformer and is less likely to require expansion of a transmission line.

The second key metric, the correct matching of the input voltage window, requires consideration of how the voltage output of the PV array will change with irradiance and temperature. As temperature increases, voltage decreases by about 0.5 percent/°C for crystalline silicon. Given that ambient temperatures may vary by > 40°C during a year and that in full sunlight modules commonly operate at 25°C above ambient temperature, the voltage from the PV array can easily vary by more than 25 percent. The system designer must consider the local weather extremes when matching the inverter's input voltage window to the PV array output. Examples of possible extreme situations are included in Table 6.4.

Table 6.4. Example of Voltage Variation Expected for PV Array (assumes −0.5 percent/°C coefficient).

Ambient Temperature	Module Temperature	Relative Voltage	Condition
25°C	25°C	100%	Flash measurement used for nameplate value
25°C	50°C	87.5%	Common temperature with common temperature increase for a module using open-rack mount
45°C	95°C	65%	Hot day with temperature increase expected for module mounted directly on roof
−10°C	0°C	112.5%	Cold day with minimal module temperature increase because of low irradiance and high wind

6.2.3.2 Types of Grid-Connected Inverters

Power-conversion electronics are categorized as central inverters, string inverters, microinverters, and optimizers (DC-DC converters), as described in Table 6.5 and the following pages. Examples are shown in Figure 6.19–6.22. Figure 6.19 shows a set of two ABB inverters installed by Solar City on a residential building. Figure 6.20 shows a set of SMA inverters installed with the Solyndra modules shown in Figure 6.4. Note that inverters can easily overheat, so manufacturers may note that the warranty is void if string inverters are not installed in the shade, as shown in Figure 6.20 (left). Central inverters are typically installed in air-conditioned sheds to avoid overheating.

A residential rooftop system using microinverters is shown in Figure 6.21. The modules are mounted just off the roof to allow air flow (cooling). The microinverters are tucked between the modules and the roof, as shown in the lower image in Figure 6.21. The system with the microinverters does not require a string inverter, but it does use an electrical box for metering, as shown in Figure 6.22. Note the rapid shutdown breaker switch shown in Figure 6.22. The rapid shutdown breaker is turned off in the case of fire to prevent exposing firefighters to high voltages. Throwing this breaker reduces the voltage at the panel level even when the sun is shining.

Table 6.5. Inverter Summary.

Type of Inverter	Typical Size	Typical Price	Application	Comment	Pro	Con
Central	1–10 MW	$0.07/W	Very large projects	Usually maintained by replacing components instead of replacing the entire inverter	Cheapest	Difficult to maintain parts; large loss of output if repair is slow because a single outage affects a large number of modules
String (commercial)	50–250 kW	$0.08/W	Commercial systems	Used for large projects	Low cost	May be difficult to maintain parts
String (residential)	2–5 kW	$0.15/W	Residential	Used for small projects	Reasonable compromise on cost and convenience	Need to maintain multiple sizes of string inverters to accommodate systems that may range from 2–10 kW
Microinverter	0.2–0.5 kW	$0.34/W	Residential	Replacing string inverters for residential	Shade tolerant, modularity simplifies design (can drive to any house and install a solar system using one type of microinverter)	Most expensive
Optimizer + simplified string inverter	0.2–0.5 kW	$0.34/W	Residential	Recently gained market share	Shade tolerant, modularity simplifies design; is competing successfully with microinverters	Most expensive

Figure 6.19. Two string inverters. Photo credit: Gabriel Llamas.

Figure 6.20. SMA string inverters. Photo credit: Kurtz.

Figure 6.21. System with microinverters (top); microinverter between module and roof (bottom).
Photo credit: Kurtz.

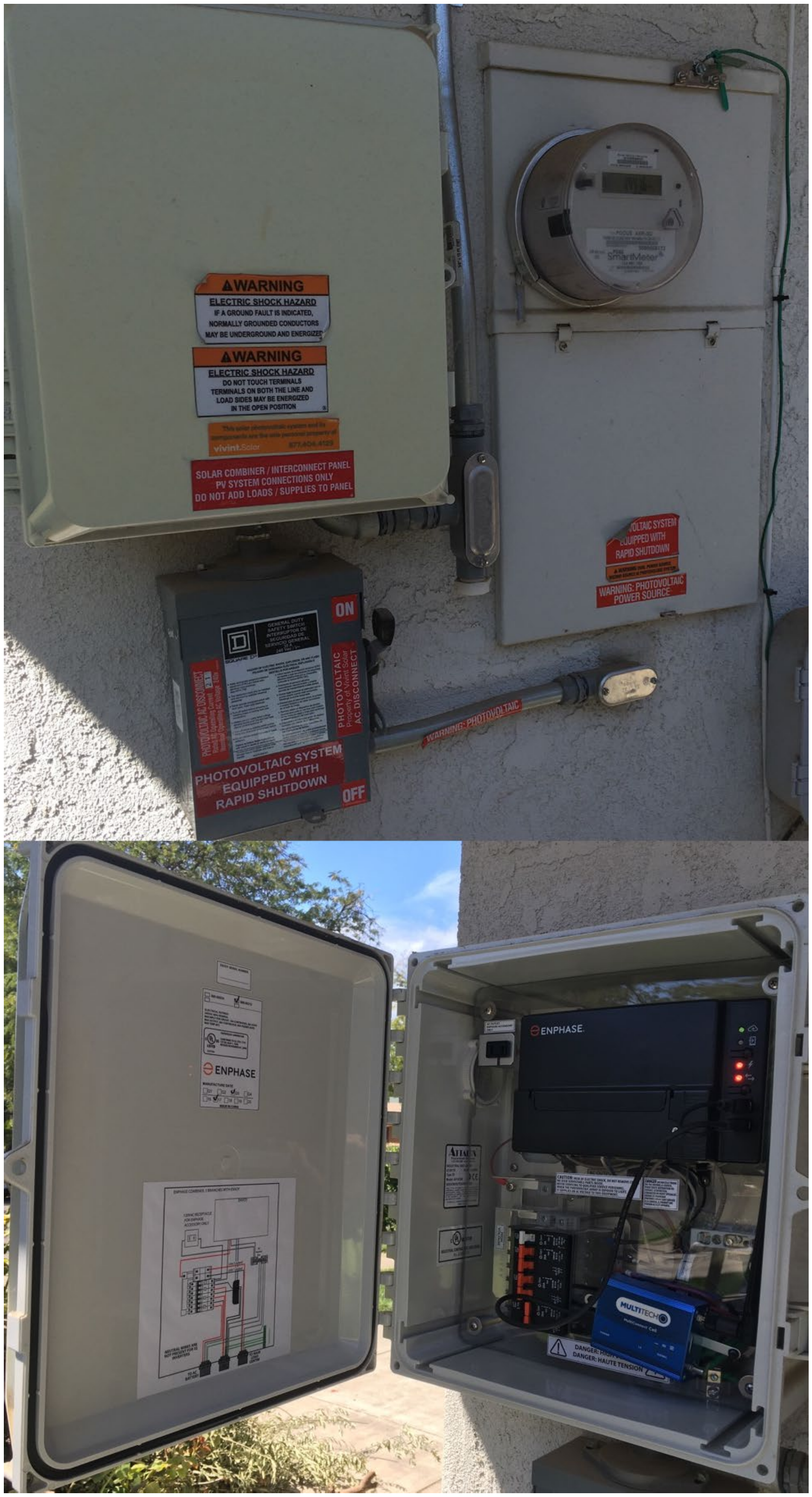


Figure 6.22. Modern interconnect for system with microinverters. Photo credit: Kurtz.

Central inverters can handle 1 MW or more of power in a single inverter. Central inverters are less costly per watt than other inverters, so they are attractive for large systems. This type of installation is recommended for large-scale applications that benefit from the low upfront cost. They can also benefit from being repaired by replacing a single component within the inverter rather than replacing the entire inverter, as is common for smaller inverters. However, when a central inverter fails, the electricity generation stops for a large part of the system. It can be prohibitively expensive to maintain an appropriate supply of spare parts, especially because designs are changing quickly and central inverters are made in much smaller numbers than string inverters, so it is difficult to stock spare parts for all types of failures. PV system owners are sometimes frustrated when inverters are down for months and the lost revenue builds quickly, so central inverters have fallen out of favor in many places. Nevertheless, for a 100-MW system, using one hundred 1-MW inverters could make sense because then a single pool of spare parts can be maintained for the entire system.

When string inverters are used, each string of modules is connected to a single inverter. For the reasons described above, some utility-scale systems are moving toward using string inverters. Historically, most residential systems used a single string inverter. Reliability may be improved when many identical inverters are used, and a failed string inverter is quickly replaced with a spare. If one inverter fails, the other strings continue producing electricity, so a failure is less serious than in the case of a central inverter. However, as in the case of the central inverter, the designs of the string inverters are evolving quickly, and a system installed in stages could easily use different models of inverters for different parts of the system, increasing the number of string inverters needed in the spares inventory. Figure 6.23 shows the nameplate for the pair of inverters pictured in Figure 6.19. It provides the DC rating as well as the AC rating. The operating voltage range is specified, enabling operation over a broad range of conditions (see Table 6.4). A string of solar modules will only produce as much current as the least productive module. If one or more of the solar modules are shaded during any part of the day, the power output from that entire string will be reduced. For this reason, if the solar modules are installed facing different directions, a string inverter is probably not a good choice.

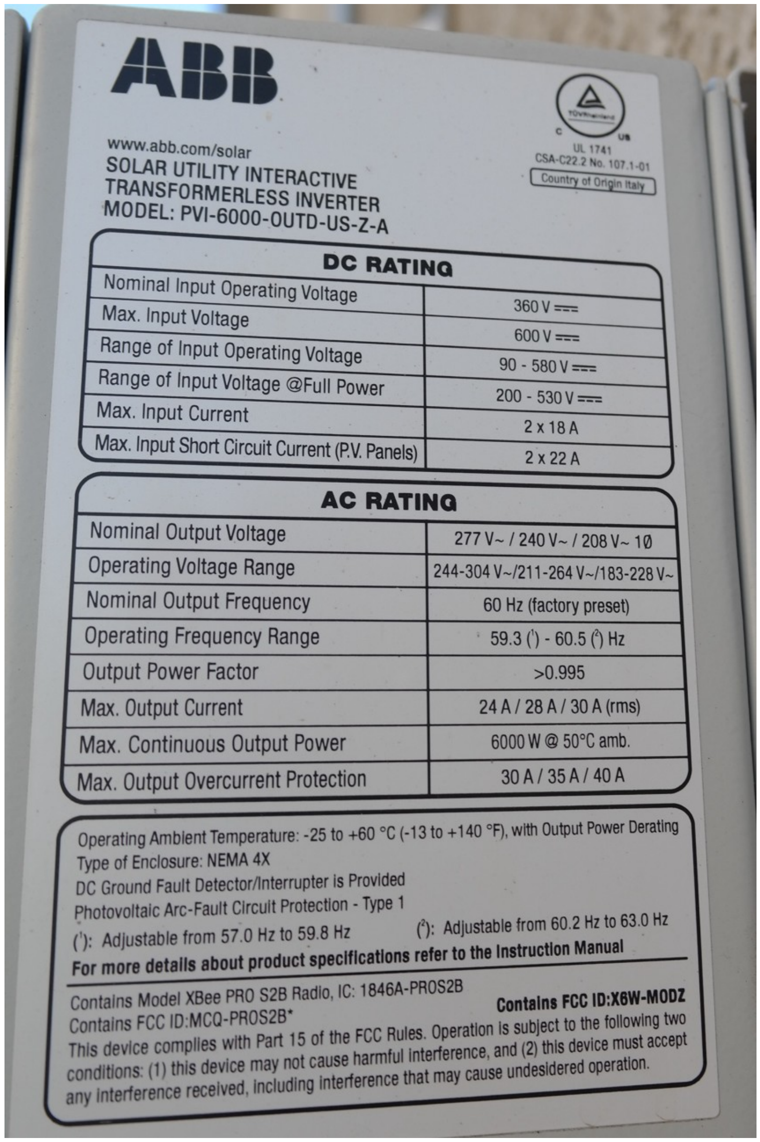


Figure 6.23. Nameplate for 6-kW string inverter that has two input circuits (see Figure 6.19).
Photo credit: Llamas.

Microinverters and DC-DC power optimizers are two options in today's market for module-level power electronics (MLPEs). In a system with microinverters, the function of converting the DC electricity to AC electricity is split into many small inverters. The microinverters are installed under every solar module and convert the electricity from DC to AC right under the module. All microinverters are connected in parallel. The microinverters match the voltage of the local AC circuit, and therefore they can be engineered to synchronously inject current into the grid or the local AC circuit at the same time in parallel. When one module gets shaded, it does not affect the performance of other modules because it is not connected in series with them. Microinverters offer a flexible configuration since solar modules can be installed in various angles and orientations. Microinverters are gaining popularity, especially in residential solar applications, but they are more expensive than string inverters. Microinverters simplify design and installation of a system because the installation contractor only needs to stock one microinverter model and one solar module model. This requires less inventory than when string inverters are used because string inverters must be selected to match the number of modules in the system. If a residential system includes modules on roof sections with different orientations, a different string inverter may be needed for each roof section. The installation contractor either needs to design the details of a system in advance and order the correct string inverters or stock many sizes of string inverters. If microinverters are used, the installation contractor can show up at the job site and decide after arriving how many modules to place on each roof section without needing to order string inverters of the correct sizes. Also, microinverters may (a) simplify system wiring since all of the field wiring is AC, which most electrical contractors are familiar with; and (b) increase safety since there is no high-voltage DC and the AC from the microinverters should shut off as soon as the utility lines are shut off in an emergency.

DC-DC power optimizers have captured market share from microinverters in recent years. This system splits the traditional inverters into two products: a DC-DC power optimizer and a simplified inverter. Power optimizers are located under each module, turning them into "intelligent" modules. The cost of DC-DC converters has dropped partially because of their widespread use in consumer products like laptops, for which it is essential to convert the ever-changing output voltage of a battery to a stable voltage to drive the device. There are many types of DC-DC converters that can be designed to match voltages (for parallel connection) or match currents (for series connection). Some module manufacturers have embedded the DC-DC converters within the module itself (see Figure 6.24, which shows two devices between the cells). However, it is more common today for them to be installed at the module level, usually external to and removable from the module. An example of a module built to have the "smart" electronics as part of the module is shown in Figure 6.25. By using module-level maximum-power-point tracking and real-time adjustments of current and voltages, the power optimizers maximize system output to the optimal working point of each module. Then, the optimized DC output is sent to a simplified inverter that only needs to convert DC to AC without needing to maximum-power-point track. When one or more modules are shaded or face different directions, the performance of each string is optimized such that the underperforming modules do not affect the output of the other modules in the string. This type of installation is commonly used on residential systems today and is recommended wherever there will be frequent shading or mismatch between the currents generated by modules within a string.

A great benefit of systems with MLPEs is that the performance of each module can be monitored individually. The data are sent to a database, and authorized users can log in to a website to view the status of the system. This information is very helpful for maintenance. Overall, systems with MLPEs are very efficient, and their prices are falling because their use is rapidly increasing.

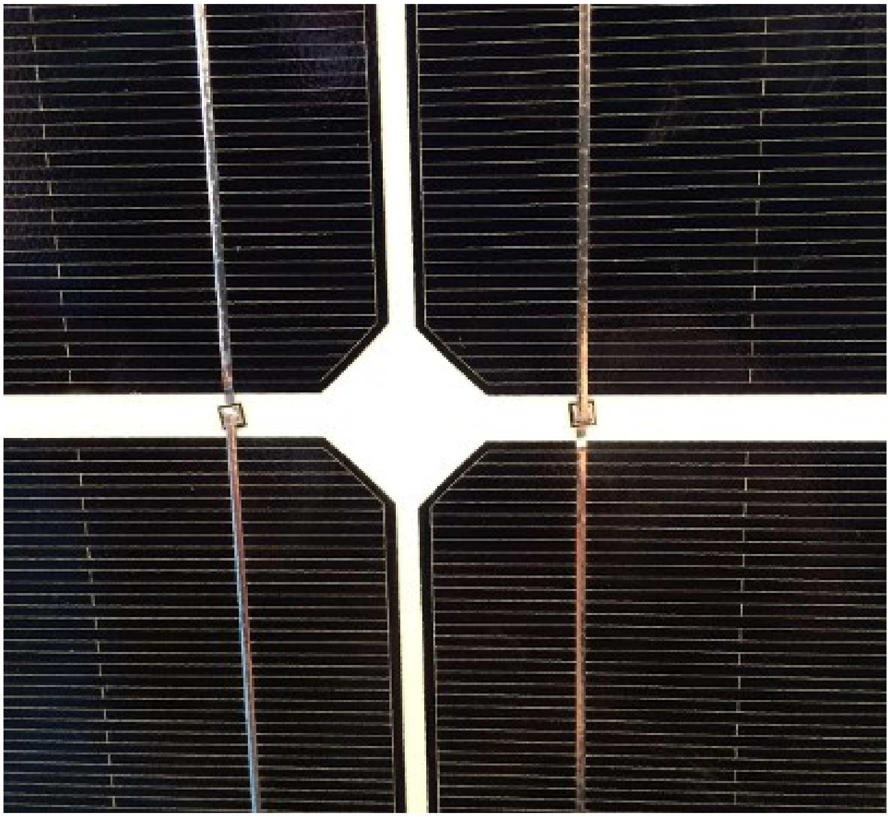


Figure 6.24. Example of optimizers embedded in module.

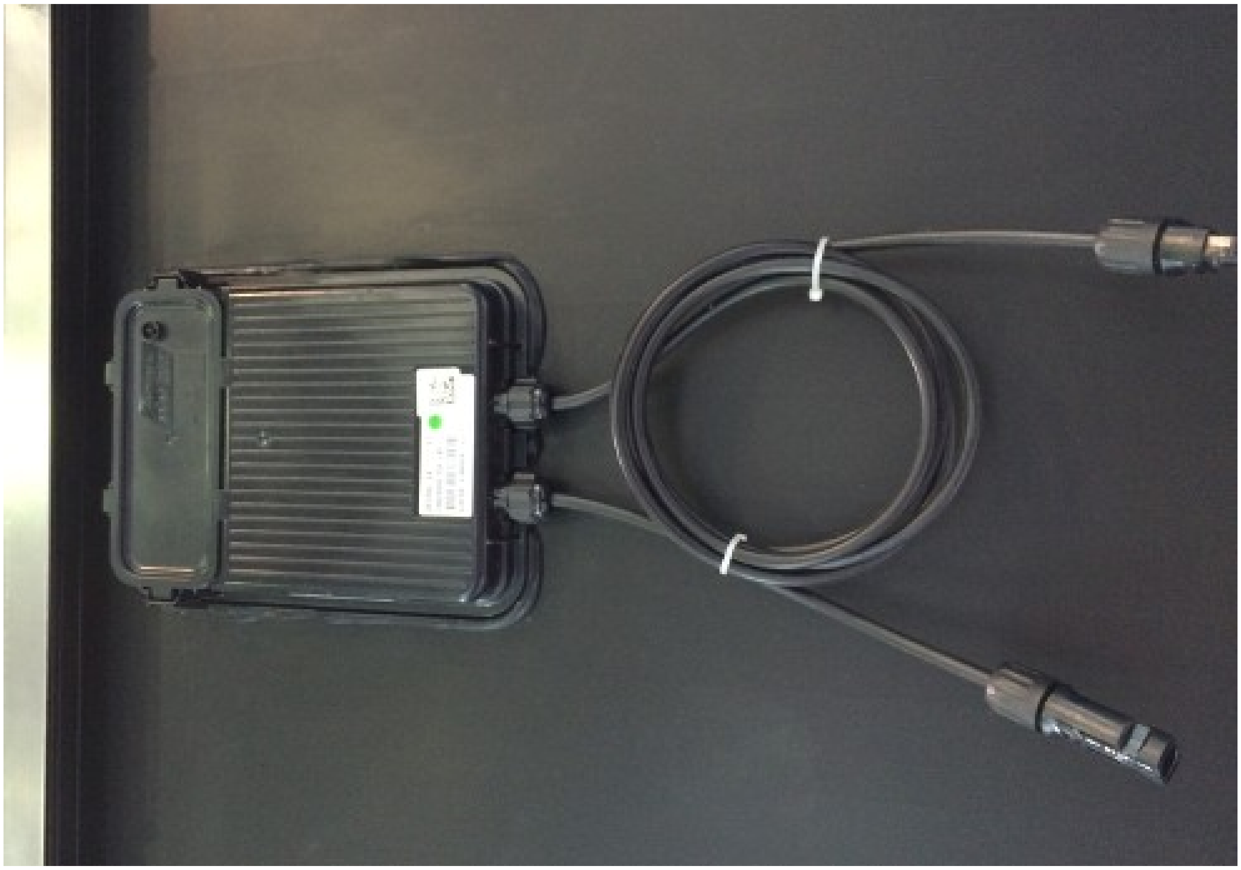


Figure 6.25. Example of "smart" module with electronics in junction box.

6.2.4 Module-Connection Considerations

6.2.4.1 Conductor Cost Considerations

PV installations utilize the same electrical conductors (wires) as other electrical installations, most commonly copper. Aluminum is cheaper than copper but does not conduct electricity nearly as well and will result in more lost energy through resistance. There is a trade-off between cost and performance when selecting the size of the conductor. The minimum size conductor is determined by code for a solar system, just as for conductors in any building, but losses may be reduced by using larger conductors if the added cost is not a concern.

The share of the total cost of the system for the conductors is typically included in the electrical balance of the system (BOS). For 2018, BOS cost was around \$0.31/W_{DC} for residential systems and \$0.17/ W_{DC} for a fixed system with 5 MW of rated capacity, and it can go as low as \$0.08 for a 100-MW system. As the system size increases, the conductors become cheaper due to economies of scale. Furthermore, by increasing the total voltage of the system (from 1000 V to 1500 V), the conductor cost can be reduced by around 19 percent (Fu et al. 2018).

6.2.4.2 Conductor Performance and Safety Considerations

In a PV installation—like other electrical installations—conductors are fundamental to achieving optimal performance. Depending on the design of the system, the number, size, and length of the conductors will vary. However, PV arrays must have at least three conductors (color coded or marked) to collect the positive, negative, and reference ground. The conductors utilized in PV plants should match the solar modules' lifetime. Since PV modules are exposed to a variety of external conditions, such as high temperature and UV irradiation, the conductors must be rated for these conditions too. IEC 60364-7-712 and IEC 62548 standards are guidelines for connecting PV modules that take into account both system safety and optimization of performance.

All electrical conductors have a rated maximum current and maximum voltage. These limits indicate the working range to ensure the conductor's proper functioning without damaging the conductor itself or the insulator coating. Multiple parameters affect the sizing of the conductor, such as the resistance of the conductor (which varies with length), PV module electrical output (which varies with conditions), design of the system, weather conditions, site conditions (e.g., direct burial or open), and state and local regulations. Furthermore, the NFPA 70 Code established that all conductors that carry current must be copper or aluminum.

Conductors for PV installations falls into three main categories: DC electrical conductors, AC conductors, and conductors for system grounding.

The DC conductors include all the conductors between the modules and the inverters, where the objective is to move the DC electricity output from the modules to the inverter. PV modules have two cables (positive and negative) to extract the current. Typically, the length of this cable is long enough to allow connecting two solar modules in series, but most of the time it is not long enough to reach the inverter. Conductors used to connect the system to the inverter should withstand relevant temperatures and UV radiation. Caltrans' extensive experience with outdoor electrical applications will be useful in ensuring that the selected conductors will survive local conditions.

Cable management is a critical detail in PV system assembly. Cables that are stretched too tight, flop in the breeze, or rub on rough edges often lead to failures that can be expensive to fix as well as pose a potential risk of fire.

NEC 690.8(B) mandates that the current capacity of the conductors for DC connections should be 56 percent greater than the short-circuit current of the module or string, before the applications of correction factors (current capacity of wiring > 1.56 I_{sc}). For ambient temperature other than 30°C, the allowable ampacity should be calculated with the appropriate correction factor in NEC 310.15(B). NEC does not dictate minimum losses in DC wiring. However, NREL suggests that the output current from the module typically reaches the inverter's input with losses around 2 percent (or lower) (NREL 2020b).

The AC conductors are used on the grid side of the inverter and use standard requirements for electricians familiar with grid connections. For a PV system using microinverters, all of the system wiring is AC.

Grounding of PV modules is required for metallic framed modules. Care must be taken in the choice of hardware for the grounding since small leakage currents drive corrosion that can be costly to fix. While Caltrans is very familiar with precautions needed to prevent galvanic corrosion of bridges and other metallic structures, the grounding of a solar system can be more problematic because the solar system is generating voltages that can drive electro-chemical reactions. Although solar modules are designed to be insulating between the active circuit and the outside of the package, even tiny currents can cause problematic corrosion, as highlighted in the *Follow-Up Interview Summary* document. Often, the problem arises because of the choice of metals used for mounting the ground wire. Corrosion occurs slowly but surely at the point of connection as a trickle of current flows every day of the year. Therefore, careful selection of all hardware in the ground path is important.

6.2.5 Voltage Considerations

The open-circuit voltage, V_{oc}, is the maximum output of the PV module or modules when connected in series. Depending on the desired output power, the V_{oc} usually ranges from 400 V to 1500 V for medium- to large-scale applications. However, the operating voltage should be less than the maximum voltage rating of the components.

The maximum allowable voltage of the system is usually a number provided by the manufacturer of the PV module or inverter. All DC components should be rated within the range of the voltage limits. For example, if the module rating is 1000 V, the V_{oc} of the system should not exceed that number in the most extreme case, which is assessed for the lowest temperature recorded at the site. Occurrence of voltages above the maximum rated voltage could result in arcing or other damage.

6.2.5.1 Trend Toward Higher Voltages

As the applications of solar modules have changed, there is an ongoing trend to increase the system voltage. At higher voltage, the transmission of electricity becomes more efficient by reducing the resistive losses and enabling use of thinner conductors.

6.2.5.2 Risk of Higher Voltages

High-voltage systems require use of personal protective equipment and safety precautions, as are standardly used by electricians for the relevant hazard class.

In the last 10 years, solar modules have been redesigned to address a failure mechanism, commonly called potential-induced degradation (PID), that is related to the voltage generated by the solar system. PID damaged many modules because the voltage generated by the solar system itself caused damage. Historically, most[7] solar systems have operated with the DC voltage positive to ground (the most negative module in the string of modules was connected to ground, while the most positive module operated at a voltage well above the earth ground). PID occurs when transformerless inverters allow the system to be wired without a defined grounding of the active circuit (the frames of the modules are still grounded, but the circuit itself floats). Depending on whether the circuit then operates positive or negative to ground, the glass front sheet may conduct some current, especially in moist conditions. Although glass is often viewed as an insulator, it can conduct some current, especially when warm and wet, so for very high-voltage systems, that leakage current is measurable. It is believed that sodium in the glass is driven into the solar cells and causes them to degrade. PID was first observed in fielded systems. Modules are now tested for their susceptibility to PID, so it is less likely to be a

[7] SunPower systems were, historically, the exception. However, SunPower today can be either positive or negative to ground.

problem in the future, but it highlights how systems that operate at very high voltages can develop unexpected new problems.

As the market moves toward higher voltages, there is a concern about the safety of the PV system. While it is true that high voltage/current can inflict harm if someone comes in direct contact, most of the installations isolate the connectors and components that could represent a risk.

Large power plants use inverters that detect arc faults and ground faults and shut off in a protective mode. For electricians who are accustomed to working with AC electricity, it is important to realize that DC arcs are much more difficult to extinguish because the arcing is continuous, while an AC arc stops and starts 120 times per second.

Rooftop PV systems may include safety mechanisms to shut off the power plant during an emergency. The NEC now requires systems to be fitted with such safety devices or by a safe system as defined by UL, so that if there is a fire, the voltage can be reduced to a safe level. Power plants should restrict access to any part of the electrical system that could pose a shock or arc flash hazard.

6.3 Grid Connection

6.3.1 Physical/Technical Considerations

One of the most important considerations in selecting a site and designing a solar system is the availability of connection to the grid. As Caltrans is well aware, if an underground connection is needed, the cost can be quite high, especially if a roadway excavation is needed. Transmission and distribution lines also vary in voltage, sometimes requiring the addition of an expensive transformer to achieve the desired voltage. Typically, the utility will desire to be involved in the design of the grid connection and will want to install a meter in order to account for the current flow of electricity both drawn from the grid and supplied to the grid. It should not be assumed that electricity may be freely transmitted from one location to another. Each line has a rated capacity, and the utility may already be using a line at its rated capacity. Thus, permission from the utility to connect to the grid should be one of the first things to be explored when planning a new system.

6.3.2 Contractual Consideration

Permission from the utility to connect to the grid is likely to be accompanied by a contractual agreement that will be negotiated either by Caltrans or by one of Caltrans' partners. Various contractual options are described in the *Financial Opportunities Assessment*.

7 CASE STUDIES

This section provides a summary of two case studies that highlight the required steps and calculations for a successful solar project implementation. Case 1 focuses on a solar system designed to support a local load without nearby access to the electric grid, and Case 2 focuses on a solar system designed to service a collection of loads with access to the electric grid under Rule 21 Net Energy Metering Aggregation, Phase 2 (NEM2A).

Disclaimer: Two case studies are provided only to illustrate the usage of the best practices summary. There is no current effort within Caltrans to plan, design, or build either case study.

7.1 Case 1: Local Load without Nearby Grid

7.1.1 Case Definition

7.1.1.1 Assumptions

Planning has been completed for this project, and this effort has been programmed. Agreements have been made with external agencies to proceed with the project. NEPA/CEQA clearances have been acquired, and all work will be completed within the existing state right-of-way.

7.1.1.2 Project Scope of Work

The intent of the solar project is to provide utility-grade solar power and solar battery backup for 96 hours on SR-3 in Siskiyou County at postmile 0.43, milepost 89.89, longitude/latitude (−122.69777, 41.27598), elevation 5401 ft, for the following loads:

- ITS cabinet, consisting of a CCTV, video encoder, networking and communication equipment, heater, and inverter/battery backup system. Power needs: 120 VAC, 2145 VA continuous. There are some reactive loads within this system.

- RWIS cabinet, consisting of controller, sensors, and other miscellaneous equipment. Power needs: 120 VAC, 450 VA continuous. There are some reactive loads within this system.

- Radio communication system, consisting of equipment that supports the Caltrans 800-MHz radio system. Power needs: 120 VAC, 2900 VA continuous. There are some reactive loads within this system.

- Hiker kiosk, consisting of light-emitting diode (LED) lighting system and USB charging stations. Power needs: 120 VAC, 300 VA; lighting on from dusk to dawn, charging station continuous. There are some reactive loads within this system.

- Highway lighting, consisting of one LED luminaire and photo electric unit. Power needs 120 VAC, 120 W from dusk to dawn.

- Highway flashing beacon system, consisting of two 12-inch yellow LED lamp modules and related controller system. Duty cycle of each beacon is 50 percent, alternating between the two lamps. Power needs: 120 VAC, 100 W continuous.
- System reserve—maintenance and other Caltrans staff desire a 20 percent overall system reserve to allow for test equipment and other loads to be determined.

The solar modules should be located in a manner to avoid snowplow piling and designed in such a manner to efficiently deal with snow loading and recovery. The solar battery backup system should be located coincidently with the solar modules' infrastructure. If the solar system/battery backup system needs environmental conditioning for proper operation, this will need to be considered as part of the overall load of the system.

7.1.1.3 Description of Area

The Scott Mountain Summit at the Pacific Crest Trail crossing was chosen for the location. During the winter, there are high snow loads in this area, and major storms lasting four to five days are common. Snow drifts and snowplow piling are also common occurrences. Commercial, utility-grade power is not accessible in this location. Figure 7.1 to 7.4 provide various views of the project location.

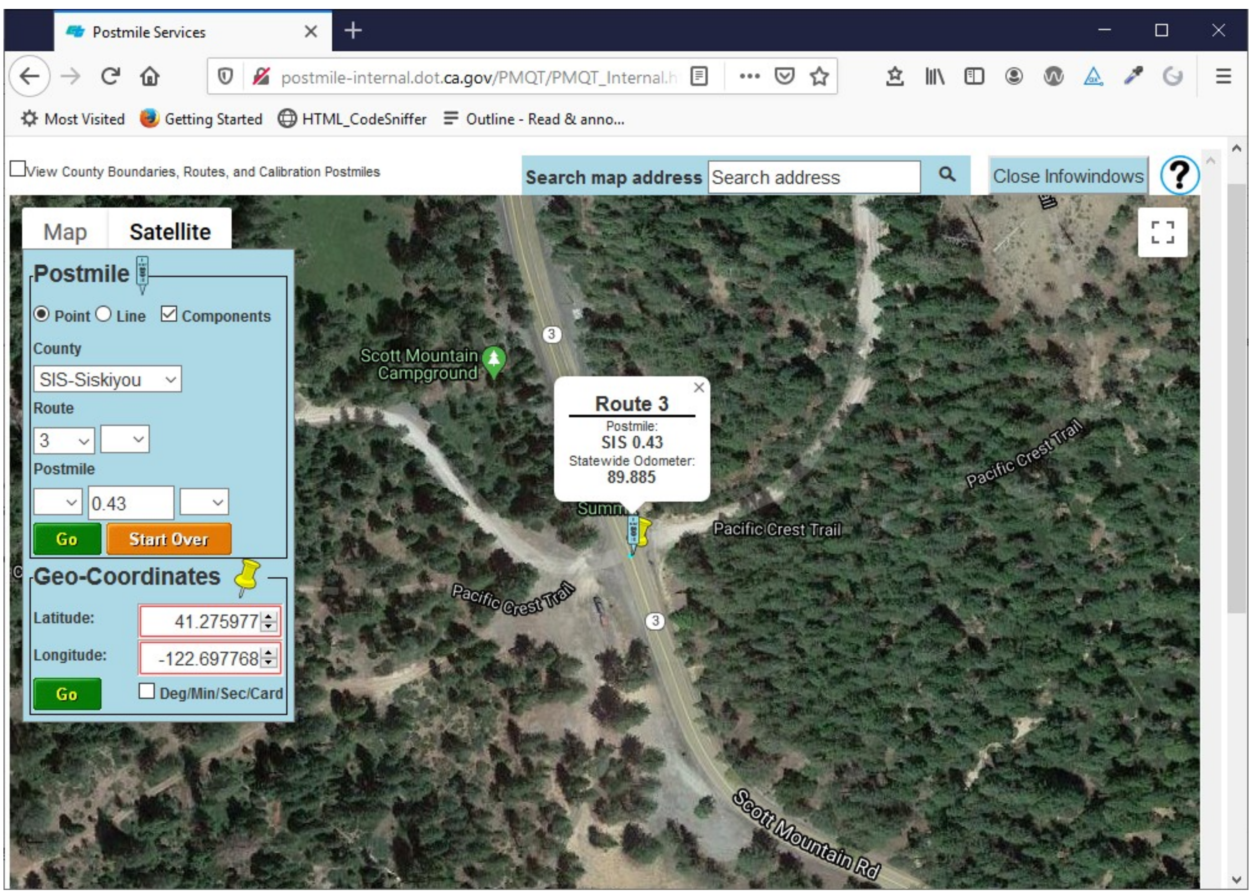


Figure 7.1. Satellite view of Case 1 location.

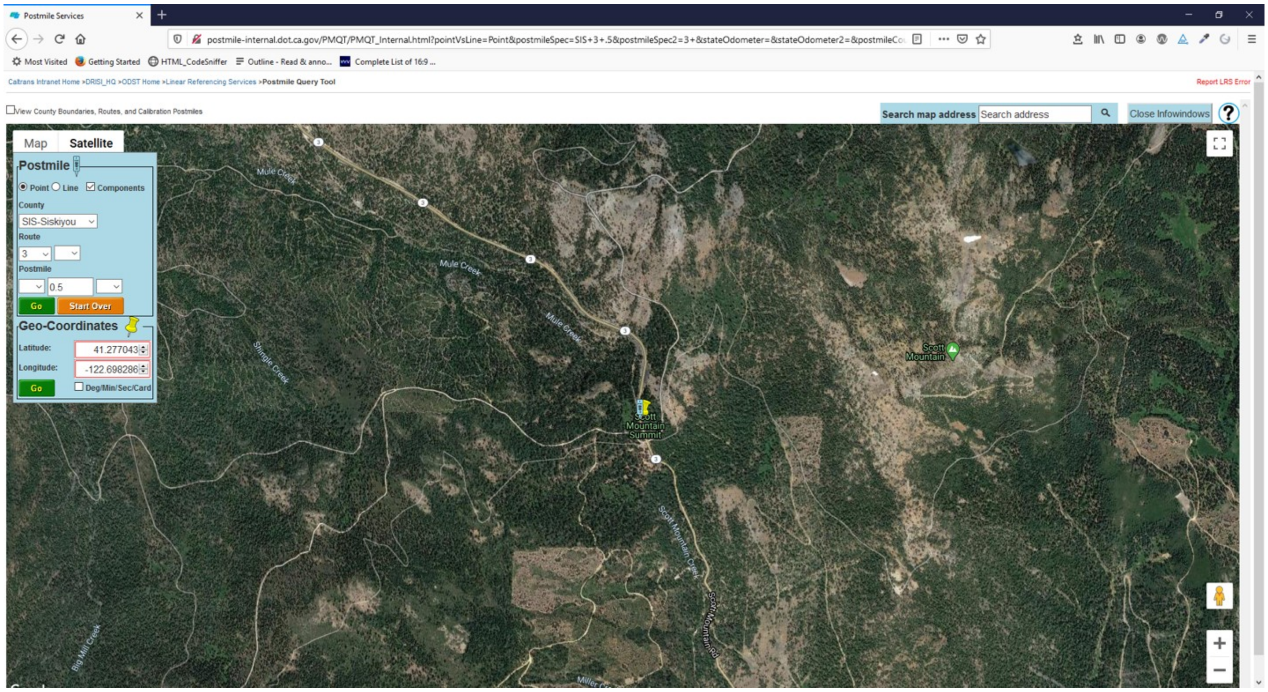


Figure 7.2. Larger satellite view of Case 1 location.

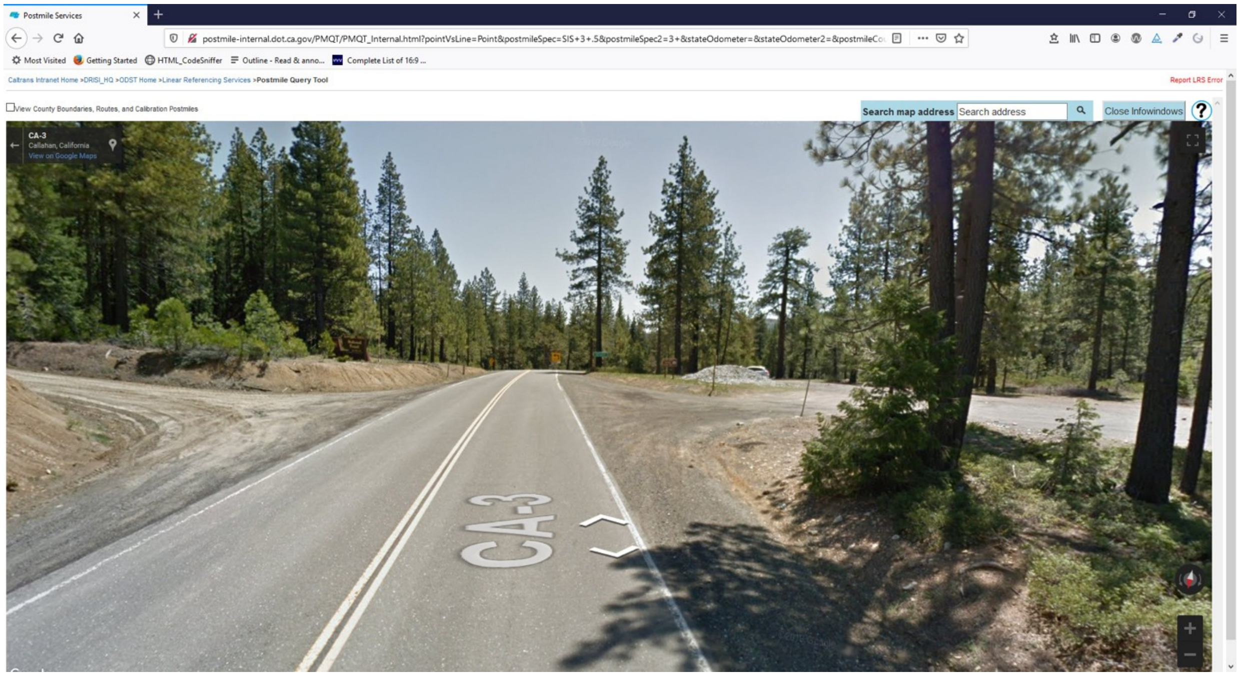


Figure 7.3. Ground view of Case 1, looking in the southbound direction.

Figure 7.4. Ground view of Case 1, looking in the northbound direction.

7.1.2 *Case Analysis—Part 1: Determine the Power and Energy Requirements*

The solar system will require the following system components:

1. Solar modules sized to deliver electricity to meet the load and keep the batteries charged.

2. Batteries with adequate backup storage.

3. Power electronics to select whether the solar electricity is directed to the batteries or to the load and whether the battery is charging or discharging, as well as to convert DC to AC.

The first step in the system design process is to analyze the estimated loads, as detailed in the project scope of work above. Table 7.1 summarizes the loads and the associated key calculations.

Table 7.1. Case 1 Load Summary.

Load	Voltage	Power	Duration
ITS cabinet	120 VAC	2,145 VA	Continuous
RWIS cabinet	120 VAC	450 VA	Continuous
Radio communications	120 VAC	2,900 VA	Continuous
Hiker kiosk (LED lighting and USB charging)	120 VAC	300 VA	LED: dusk to dawn Charging: continuous
Highway lighting	120 VAC	120 W	Dusk to dawn
Highway flashing beacon	120 VAC	100 W	Continuous
Total for components	120 VAC	5,595 VA + 420 VA = 6,015 VA	Continuous Dusk to dawn Maximum total
System reserve (20% of specified components)	120 VAC	1,203 VA	Continuous
Total maximum load with reserve	120 VAC	7,218 VA	Continuous
Daily maximum energy = 24 h × 7,218 VA		173 kWh/day	
Backup energy for 96 hours = 96 h × 7,218 VA		693 kWh	
Minimum backup energy Adjust for battery efficiency = 693 kWh/0.9		770 kWh	

Notes:

- Given that the dusk-to-dawn load is < 7 percent of the total load, a worst-case analysis is given by taking these as continuous loads, simplifying the calculation. This may overstate the total demand by about 3 percent, depending on what fraction of the USB charging is used during the day.
- Some reactive loads are mentioned, but details are not given. A common assumption may be a 90 percent power factor. The power factor adjustment is omitted here, but a more conservative analysis would analyze the anticipated power factor and include it. The power factor that is observed in the final system may depend on (a) the inverter that is used and whether it has the ability to adjust to reactive loads; and (b) the load profile—if some of the hardware is stopping or starting, the power factor may vary from moment to moment.
- The backup energy is increased to account for 90 percent efficiency for the battery discharge cycle. This may underestimate the losses, depending on the battery efficiency.
- The inverter efficiency is included in the PVWatts calculation, so it is not included here, but the inverter losses may add to the assumed battery discharge loss of 10 percent.

The conclusions of this analysis are that the PV system needs to be sized to deliver 173 kWh/day while keeping the batteries charged and that the batteries need to maintain a charge of 770 kWh in order to meet the 96-hour reserve energy specification. On a cloudy day, the system may not generate enough power to recharge the batteries by the amount of energy that is used, so the system will discharge. The 96 hours was an estimate of the time that might go by without sunshine and will depend on the weather.

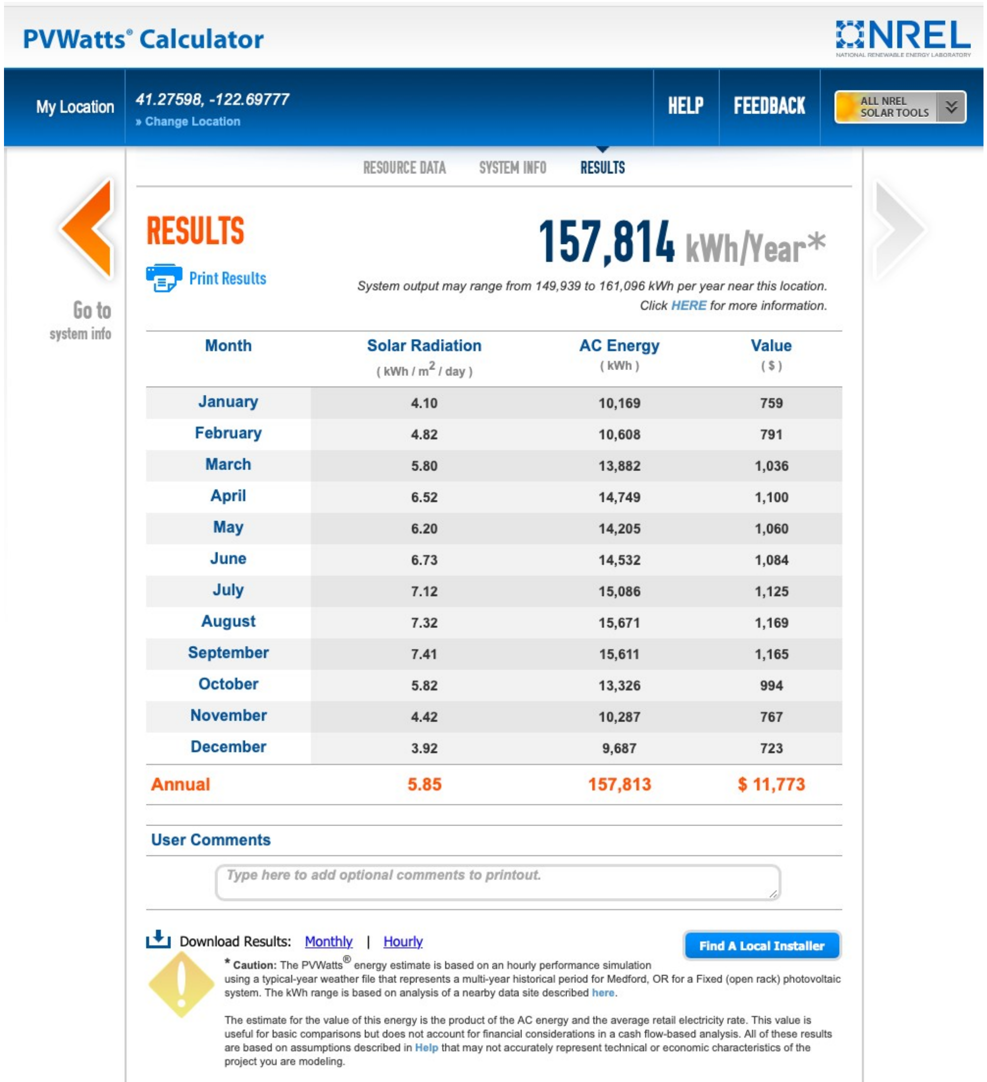
7.1.3 Case Analysis—Part 2: Determine the Solar Resource for this Location

By entering the latitude and longitude into PVWatts, and, for simplicity, assuming a 100-kW system, engineers can model the output of a system. The optimal design for this off-grid system will be a larger tilt than the default PVWatts because for a stand-alone system, the design is optimized for the worst month of the year, so the 20-degree tilt default was increased to 45 degrees, as summarized in Table 7.2. The output is summarized in Figure 7.5.

Table 7.2. Input Assumptions for Initial PVWatts Simulation for Case 1.

Parameter	**Value(s)**
Requested Location	41.27598, −122.69777
Location	Latitude, Longitude: 41.29, −122.7
Latitude (deg N)	41.29
Longitude (deg W)	122.7
Elevation (m)	1459.15002
DC System Size (kW)	100
Module Type	Standard
Array Type	Fixed (open rack)
Array Tilt (deg)	45
Array Azimuth (deg)	180 (south facing)
System Losses	14.08 (PVWatts default)
Inverter Efficiency	96
DC-to-AC Size Ratio	1.2 (this may be adjusted depending on the power electronics)
Capacity Factor (%)	17.5 (this is calculated by PVWatts)

Note that the elevation of 1,459 m will affect the cooling of the power electronics and other components of the systems. All components should be confirmed to be specified to operate at the chosen elevation.



Month	Solar Radiation (kWh / m² / day)	AC Energy (kWh)	Value ($)
January	4.10	10,169	759
February	4.82	10,608	791
March	5.80	13,882	1,036
April	6.52	14,749	1,100
May	6.20	14,205	1,060
June	6.73	14,532	1,084
July	7.12	15,086	1,125
August	7.32	15,671	1,169
September	7.41	15,611	1,165
October	5.82	13,326	994
November	4.42	10,287	767
December	3.92	9,687	723
Annual	5.85	157,813	$ 11,773

Figure 7.5. PVWatts results for 100-kW system. The simulation used 45-degree south-facing tilt as well as all other PVWatts default conditions.

A quick analysis provides the system design that would balance the electricity generated with the electricity used for a grid-tied system over a year. To do this, note that the insolation averages 5.85 hours/day. Using the equation in Section 4.1.2:

$$\textit{Electricity estimate (kWh/d)} = \textit{System DC power rating (kW/(kW/m}^2\textit{))} \times \textit{Insolation (kWh/m}^2\textit{/d)} \times 0.8$$

$$\textit{173 kWh/d} = \textit{System DC power rating (kW/(kW/m}^2\textit{))} \times 5.85\ \textit{(kWh/m}^2\textit{/d)} \times 0.8$$

Solving for the DC power results in a rating of 37 kW. This makes sense in that the load is about 7 kW and the sun shines effectively at full brightness about 1/5 of the time, so the needed system size would be 7 kW × 5 = 35 kW. However, because the system is not grid tied, it needs to be sized for the cloudiest period of the year. The specification of the system will be highly dependent on the desired reliability.

In preparation for sizing the system to the desired reliability, engineers can download the PVWatts simulation data from the webpage shown in Figure 7.5.

7.1.4 Case Analysis—Part 3: Calculate the Reliability as a Function of System Design

Optimization of the design for a specified reliability can be completed using specialized optimization software, but the calculations can also be completed in a spreadsheet, as can be downloaded here and is further described in Section 7.3. Using the file that is generated by running PVWatts (see Figure 7.5 and Section 3), the hour-by-hour state of charge is estimated in the spreadsheet for the typical year that is used by default by PVWatts.

When evaluating the needed reliability, it is useful to consider the causes of outages. Studies consistently show that solar system failures are dominated by failures of the power electronics—typically the inverter. If the inverter fails, a full battery is useless until the inverter is fixed. This analysis assumes that the 96 hours of reserve were requested as a buffer for cloudy, snowy weather rather than hardware failures.

The PVWatts output file includes the "AC System Output (W)" in Column K based on the DC system size, which is given in cell B7 and additional design parameters. In the sample PVWatts output spreadsheet, the following information and formulas have been entered in Columns M and N:

- Total load (kW) (a constant is used for simplicity, but this could be calculated for each hour).
- Size of solar system (kW).
- Battery capacity (kWh).
- Initial battery charge (kWh).

The spreadsheet calculation then uses the following equations:

Output of solar system (kW) = AC output (W) × Size of system (kW) / DC system size (kW) / 1000 (W/kW)

Battery charge (kWh) = Previous charge (kWh) + Output of solar system (kW) × 0.9 – Load (kW) / 0.9

If Battery charge exceeds Battery capacity, then Battery charge = Battery capacity

The output of the solar system is reduced by the factor of 0.9, and the load is increased by dividing by 0.9 to reflect the energy loss associated with charging and discharging the battery. Once an exact system design is finalized, the efficiencies of the power electronics and batteries should be compared with the assumptions of PVWatts and the above. Then corrections should be applied for any significant differences.

The results of the calculations for a range of assumptions are presented in Figure 7.6 and 7.7 and summarized in Table 7.3. Modeled results for the minimum size system are shown in Figure 7.6. This design was derived by sizing the battery to provide the requested 96 hours of storage when it is full (770 kWh, as shown in Table 7.2), which will happen at dusk on all sunny days during more than half of the year. However, during the winter, the length of the day and the added clouds and fog reduce the solar resource too low to keep the battery fully charged. The system size was adjusted to keep the battery charge above zero even on the worst day of the winter, but there are multiple days in this scenario during which the battery reserve is reduced to less than 24 hours.

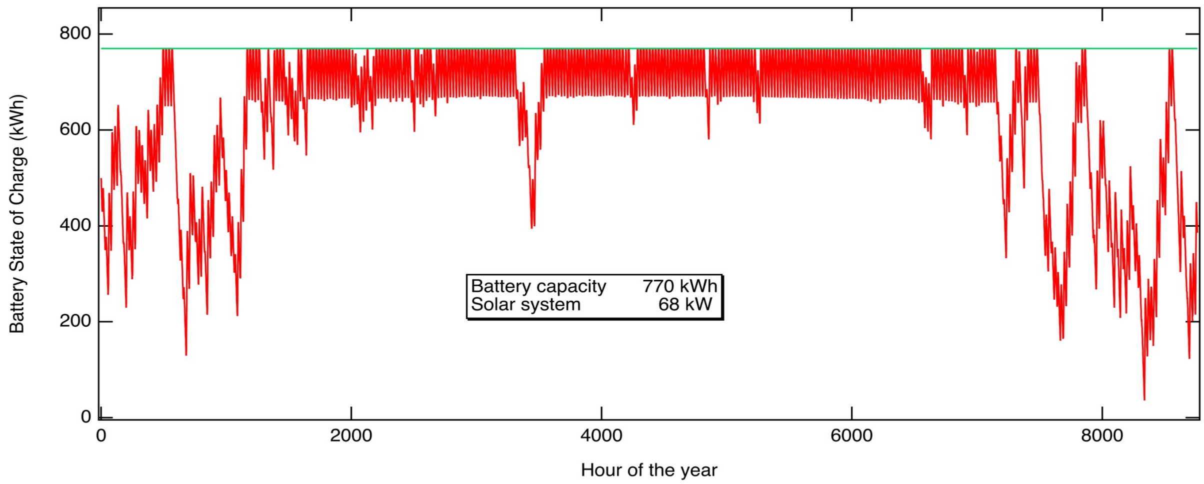


Figure 7.6. Modeled charge state of battery with minimum system size. The red trace provides the state of charge. The green line indicates the requested 96 hours of storage.

The wintertime reliability may be improved by increasing the size of the solar system. In the third simulation, the size of the solar array was doubled to 136 kW, as shown in Figure 7.7. With this design, the battery always retains more than about 50 hours of storage and is close to 96 hours more than 90 percent of the days. A thorough analysis would include running the PVWatts calculation for weather data from the cloudiest, coldest weather that has been documented at this location. These simulations predict 100 percent operability of the system in a typical year.

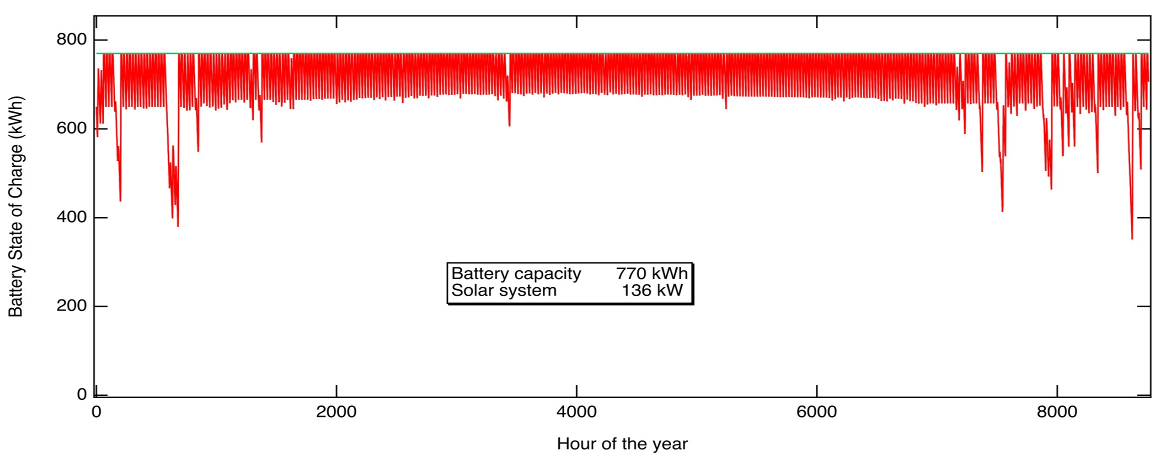


Figure 7.7. Modeled charge state of battery for second simulation. The red trace provides the state of charge. The green line indicates the requested 96 hours of storage.

The results of the simulations are summarized in Table 7.3. A column has been added to estimate the anticipated cost of each system, making the simplistic assumptions that the solar will cost $2/W and the battery will cost $0.4/Wh. These cost estimates may be adjusted depending on the style of the system and ultimately may be substantially different, so a final analysis will need to consider the available pricing. The cost is estimated to be about $0.5 million.

Table 7.3. Summary of Simulations for Case 1.

Scenario	**Battery Capacity**	**Solar System Size**	**Reliability**	**Estimated Solar System Cost**[1]
Minimum size	770 kWh	68 kW	96 h at dusk more than half of days	$444k
Double solar system	770 kWh	136 kW	96 h at dusk more than 90% of days	$580k
For comparison, not as a solution: Grid tied	0 kWh	37 kW	Grid's reliability	$74k

[1] Based on $2/W for solar and $0.4/Wh for battery.

The roughly estimated cost for the grid-tied system needed to deliver the kWh to meet the specified loads is also shown in Table 7.3. The cost of the system may be higher because of the special engineering needed if the installation contractor cannot leverage engineering from a different project. It should also be noted that TOU considerations might increase the needed system size to be able to balance the cost rather than the energy. The majority of the cost for both of the modeled systems is in the battery, but the size (and cost) of the solar system almost doubles because of needing to size the system for the worst week of the year rather than for the average performance over the year.

Accumulation of snow on the modules may prevent electricity generation even while the sun is shining. The PVWatts data for this location suggest that the temperature of the modules almost always exceeds the melting temperature when the sun is shining (see spreadsheet). However, a snow-covered module may not be warmed by the sunshine, so it may stay closer to the ambient temperature just after a snowfall. This could result in delayed melting of the snow, causing the need for more battery reserve. Additionally, battery capacity is reduced in cold weather. However, adding temperature control for the box would also increase the needed reserve, so it is unclear whether temperature control for the battery would be useful. The spreadsheet can be modified to include temperature-dependent battery function. A better solution might be to place the batteries in a buried box so that the ground helps to maintain a constant year-round temperature.

Two key design features are recommended for this off-grid system: an increased *tilt angle* and *bifacial modules*. The default tilt value of the PVWatts calculator was changed from 20 degrees to 45 degrees. The added tilt provides two primary benefits: (a) it will catch the winter sun better, increasing the electricity generation during winter months; and (b) the steeper tilt will result in the snow sliding off sooner. However, the large tilt may result in row-to-row shading that will decrease the output of the system in the winter, so care should be taken to model the final design accurately. The use of bifacial modules (modules that respond to sunlight on both the front and the back) will also be very helpful for successful operation during snowy conditions. Light that is reflected off the snow may strike the back of the solar modules and generate some electricity even on a day when the front sides of the modules are covered with snow (though while it is snowing, the irradiance is unlikely to reach a level that will allow the inverter to function). Once the sun comes out, the black backsides of the bifacial modules will warm quickly from the sunlight reflected from the snow, helping the snow to be shed very soon after the sun comes out. If problems with ice are anticipated, an even steeper tilt could be used to reduce the snow that collects on the modules, or electricity from the battery can be used to heat the panels enough to melt the snow.

The design of the system should plan on piles of snow falling from each row of modules. The tilt may be increased even more to attempt to have less snow stick to the modules, but snow may stick to even a vertical surface depending on the direction of the wind and weather conditions, and a steep tilt angle makes it more difficult to avoid row-to-row shading. An elevated structure that is taller on the north side may be very helpful to reduce row-to-row shading.

The above calculations should be modified according to the efficiency and expected lifetime of the selected batteries. The charging capacity as well as the charging/discharging efficiencies not only vary from battery to battery but also change with time, temperature, discharge depth, and rate of charging and discharging. These effects can result in a factor of 2 or even a factor of 10 change in capacity, eventually requiring replacement. Battery replacement should be planned before the battery capacity decreases to the point of delivering insufficient reliability. Some batteries are able to discharge fully, while others may be damaged by a full discharge. The efficiency and lifetime are also dependent on these factors. A charge controller that charges all of the batteries simultaneously with a trickle charge going into each battery may have different efficiency than a charge controller that selects individual batteries to charge or discharge one at a time. The power electronics should be programmed to match the requirements of the selected batteries and to reflect the latest technology. A complete analysis is beyond the scope of this study. Instead, a high-level review and some references to examples of more detailed information are provided (Davies et al. 2019; Tesla 2019; Mongird et al. 2019; Trojan Battery Company 2020).

In the early days of solar systems, off-grid systems were common and typically used lead-acid batteries. In contrast, the huge deployment of solar systems in recent years has been mostly grid tied and without batteries, limiting off-grid systems to niche applications like a solar system for a boat.

In more recent years, lithium ion batteries have advanced significantly. For mobile applications, lithium ion batteries have a key advantage because of their lighter weight. Their performance has been matured with longer lifetimes than the historical lead-acid batteries. There has been some debate about what the best storage technology for stationary applications will be. Currently, the MW-size deployments are using mostly lithium batteries, while consumer solar products (e.g., for recreational applications or off-grid residential) are more likely to still use lead-acid batteries, though this is changing. It is important to understand that the properties of batteries can vary from product to product even for the same technology. To understand this, a small example is provided. Consider that when a battery is made, the positive and negative electrodes are separated by a thin layer. If the layer is very thin, it will have a lower resistance and will be able to facilitate higher current during charging and discharging, but that same thin layer may allow the battery to slowly discharge with time. A battery that provides a high current to run a starter motor but is usually recharged every few days benefits from a thin separator between the electrodes. On the other hand, a battery that powers a smoke detector requires a very slow self-discharge in order to deliver a very low current reliably for something like 10 years. A manufacturer may develop different versions of the same battery technology for different applications; in this case, varying the thickness of the layer separating the two electrodes would differentiate products, but there are many other details of a battery design that affect its performance. When the quality control is imperfect, the properties of the battery may even be unexpected, as in the case of the Samsung battery fires.

A high-level summary of some battery types that are commonly used for solar systems is shown in Table 7.4 (Davies et al. 2019; Tesla 2019; Mongird et al. 2019; Trojan Battery Company 2020). Lithium iron phosphate batteries may have a slightly reduced risk of fire compared with lithium ion batteries made with nickel, manganese, and cobalt. Although there is not yet a clear winner for the type of battery that will be most common for solar systems, there is some evidence that lithium iron phosphate may end up being a favorite (EnerCom 2020), though one battery expert suggested that the promotion of lithium iron phosphate for stationary applications may be a result of its being unsuccessful for mobile applications.

Table 7.4. Summary of Key Battery Attributes.

Battery Type	Warranty	Efficiency	Price	Maintenance and Details
Lead-acid	3 years	50%–90%	Low	Need to add water if not sealed. Efficiency highly dependent on charge rate and temperature.
Lithium iron phosphate	10 years	80%–98%	High	Essentially no maintenance. Capacity is decreased at low temperatures. Unlikely to experience thermal runaway.
Lithium ion (Ni, Mn, Co)	10 years	80%–98%	High	Essentially no maintenance. Capacity is decreased at low temperatures. Thermal runaway can lead to fires.

7.1.5 Case Analysis—Part 4: Siting the System

Based on the analysis summary in Section 7.1.4, it can be concluded that the system must be at least 68 kW and would be better to be closer to 130 kW. Using the tool in PVWatts, engineers can estimate that a 130-kW system can be made to fit in this space if a couple of trees are cut down, as shown in Figure 7.8. However, the street view images identify that the surrounding trees are quite tall. During the winter, when the sunshine is needed most, the trees will cast the longest shadows. The easiest solution is to trim the trees. It is likely that there would be a benefit to installing the system on a raised structure so that vehicles could drive or park underneath. This would help to reduce shading, but a structure that is tall enough to avoid shading by tall trees would not be practical. An assessment of the loss in performance due to shading should be considered and alternative locations considered if the trees cannot be trimmed to avoid shading in the future. If shading must be tolerated, then this system would be a candidate for using optimizers to reduce the shading loss.

A raised structure would increase the cost of the system. On the other hand, a raised structure may be required in order to preserve the desired parking area.

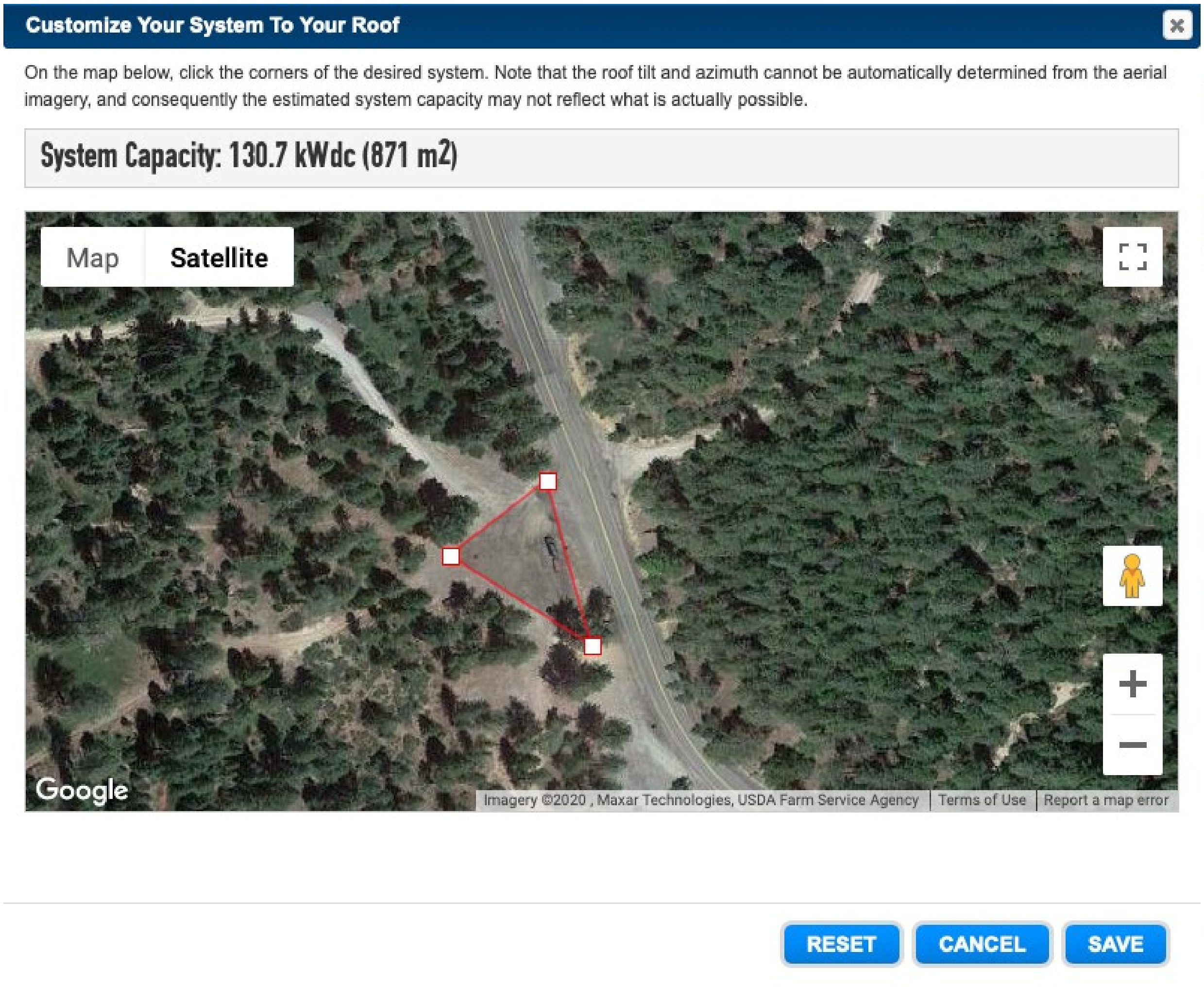


Figure 7.8. Estimation of siting of 130-kW system for Case 1.

7.1.6 Case Analysis—Part 5: Other Considerations

The preceding sections focused on calculations related to the solar resource and system size discussed in Section 4.1. The considerations addressed in Section 4.2, local off-grid, grid connection, and transmission, are not relevant to this case. The considerations discussed in Section 4.3 are summarized in Table 7.5.

Table 7.5. Practical Considerations for Case 1.

Consideration	Comments
Safety and security	The site appears to sometimes be used by hikers accessing nearby trails. It is recommended that the elevation of the system act as a shade for those who are parking and that all high-voltage elements be placed out of reach. These actions should reduce shock hazard and likelihood of vandalism. The plan needs to leave the required safe zone between the road and the system. The design should be reviewed for any potential fire risks given the wooded location.
Future plans	Unless trees can be trimmed, this system will be very close to the road. If there is the possibility of widening the road in the future, additional setback should be considered, which might, however, change anticipated shading.
Site preparation	Trees will need to be trimmed in preparation, but much of the area already appears to be flat to accommodate parking. If the system is installed on a raised structure, it may not be necessary to level the site, nor is drainage likely to be a problem (if it is not currently a problem).
Maintenance	Trees will likely need to be periodically trimmed in order to not shade the system too much, but this may be done infrequently. A raised system would not be affected by growth of grass and other weeds. A 45-degree tilt will facilitate natural cleaning of the modules, so washing is unlikely to be needed. Snow should shed naturally as soon as the sun comes out at this location, especially if bifacial modules are used. A raised system could result in additional maintenance issues, such as ice built up on the ground from snow melting off the solar modules and interfering with snow plowing.
Glint and glare	Glint and glare are unlikely to be a problem for a raised system since drivers and hikers are more likely to be looking at the road or the trail than at a reflection from the modules.

Based on the information summarized in Table 7.5, the key features of the design of this system should include:

- Bifacial modules.
- South-facing tilt of about 45 degrees.
- If budget allows, use of an elevated system to avoid issues with shading and to allow sliding snow to clear.
- Installation of battery in a protected location to avoid low-temperature operation during the winter.

7.2 Case 2: Grid-Tied System to Service Collection of Loads with Rule 21 NEM2A

7.2.1 Case Definition

The second case study is of a grid-tied system to complement Case 1, which was an off-grid system requiring storage. Rule 21 NEM2A allows an electricity customer to use net metering to reduce the customer's electricity bill by generating solar electricity for self-consumption as well as injecting surplus electricity into the grid to offset electricity needs at times when the sun is not shining. Case 2 includes a collection of loads along SR-113.

Solar customers are now required to use TOU rates (see Figure 2.4 for an example) to partially reflect the market value of the electricity at the times of generation and consumption. This case study does not include revenue analysis, which will depend on the location and the business arrangement and may be complex. For example, in addition to rates that vary with time of day, day of week, and day of year, electricity bills may include demand charges or connection fees. This case study is not intended to explore those details but to consider the sizing and siting of the system to power a collection of loads along a 10-mile corridor.

It is assumed that all of the loads are already powered by the grid (i.e., they are connected to the grid) and that the solar system can be connected to that grid. The cost and permitting required for the grid connection could easily define the practical implementation but are outside of the scope of this study.

7.2.2 Case Analysis—Part 1: Determine the Power and Energy Requirements

The loads to be powered in this case study are summarized in Table 7.6. A more comprehensive description of the loads was supplied in a spreadsheet, but the detailed descriptions are not included here for brevity and because the calculation is based on the total kWh required rather than on meeting the specific needs as a function of location and time. Note that the majority of these loads are nighttime loads, so powering them with net-metered solar electricity is effectively using the grid as a large battery.

Table 7.6. Summary of Loads in the Second Case Study.

Load Location	Service Name	Load Type	Service Daily Load (kWh)
SR-113/I-5 IC	Service 0322005R007000/ 03-SP-B-52	Luminaires (7); sign lighting (1)	11.5
	Service 0322005R007700/ 03-SP-B-53	Luminaires (5)	12.5
Main Street	Service 0322113R010102/ 03-SP-B-51	Luminaires (4); sign lighting (5)	14.8
	Service 0322113R010100	Signal (1); luminaires (2); sign lighting (1)	22.0
	Service 0322113R010101	Signal (1); luminaires (2); sign lighting (1)	22.0

Load Location	Service Name	Load Type	Service Daily Load (kWh)
Road 24—Gibson Road	Service 0322113R009236	Signal (1); luminaires (7)	25.7
	Service 0322113R009237	Luminaires (5); sign lighting (4)	14.9
	Service 0322113R009238	Signal (1); luminaires (6)	26.6
	Service 0322113R009638	Luminaires (8)	13.0
Road 25A	Service 0322113R007716	Luminaires (6)	8.0
	Service 0322113R007715	Luminaires (6)	9.5
Road 27	Service 0322113R005829	Luminaires (3)	3.6
	Service 0322113R006111	Luminaires (6)	9.5
	Service 0322113R006433	Luminaires (3)	5.4
Road 29	Service 0322113R003970/ 03-SP-B-86	Luminaires (2)	2.8
	Service 0322113R004100	Luminaires (8)	12.5
	Service 0322113R004101/ 03-SP-B-T-28	Luminaires (4)	6.3
Road 31 Covell Boulevard	Service 0322113R002040	Luminaires (5); sign lighting (2)	10.7
	Service 0322113R002041/ 0322113R002042	Cabinets (2); luminaires (10)	43.6
	Service 0322113R002320/ 03-SP-B-85	Luminaires (4)	3.6
Russell Boulevard	Service 0322113R000900/ 03-SP-B-82	Luminaires (7); sign lighting (5)	17.3
	Service 03-SP-B-83	Luminaires (5); sign lighting (3)	14.2
	Service 0322113R001080/ 03-SP-B-90	Signal (1); luminaires (1); sign lighting (6)	31.1
	Service 0322113R001081/ 03-SP-B-91	Signal (1); luminaires (1); sign lighting (3)	25.1
Hutchinson Drive	Service 0322113R000380/ 03-SP-B-T-21	Luminaires (9)	13.6
	Service 0322113R000510	Luminaires (9); sign lighting (6)	28.4
SR-113/I-80 IC	Service 23080R044002A	Luminaires (7); sign lighting (7)	28.2
	Service 23080R043404A	Luminaires (8); sign lighting (6); tunnel lighting (10); soffit/wall lighting (9)	93.4
	Service 23080R043402A	Luminaires (7); sign lighting (2)	18.8
	Service 230800042401A	Luminaires (2); sign lighting (1)	6.2
	Service 230800041902A	Luminaires (2); sign lighting (4)	12.2

Load Location	Service Name	Load Type	Service Daily Load (kWh)
	Service 230800042702A	Luminaires (2); sign lighting (1)	6.2
	Service 23113R022441A	Luminaires (5); sign lighting (2)	14.8
Total			**588**

7.2.3 *Case Analysis—Part 2: Determine the Solar Resource for this Location*

The geographical range of locations is visualized in Figure 7.9. The latitudes for these locations range from 38.513 to 38.692, while the longitudes range from −121.7767 to −121.7464. Solar resource data are available on a grid of 0.04 degrees, so these solar resource data are compared to see if there is evidence of any microclimates (Table 7.7) and final minimal variation.

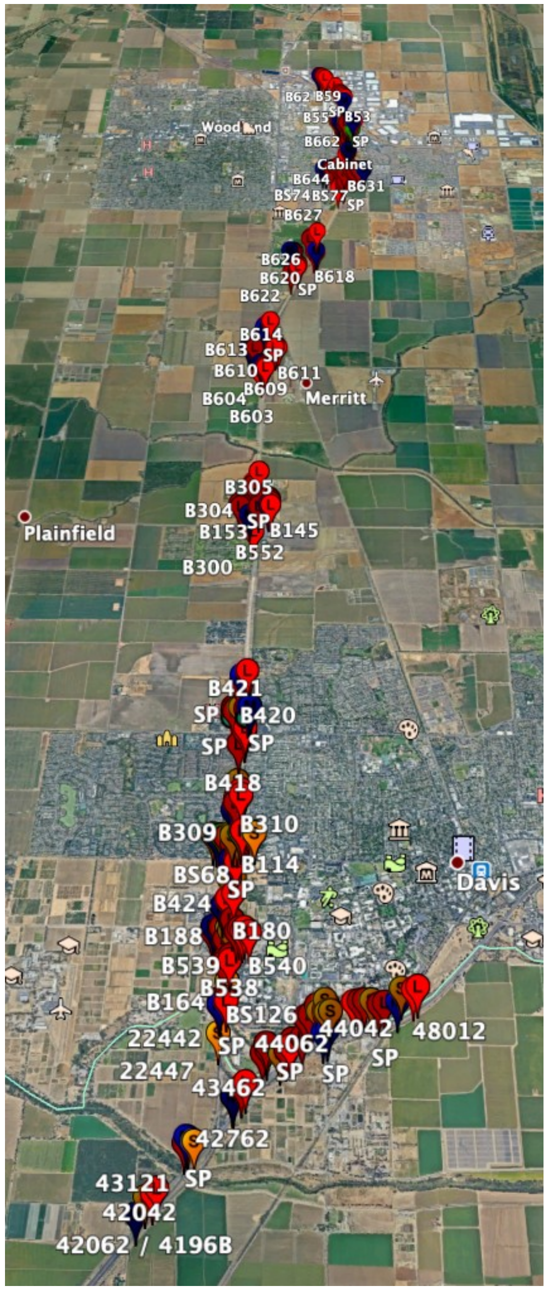


Figure 7.9. Locations of loads along SR-113 corridor for Case 2.

Table 7.7. Variation in Solar Resources along the SR-113 Corridor Shown in Figure 7.9.

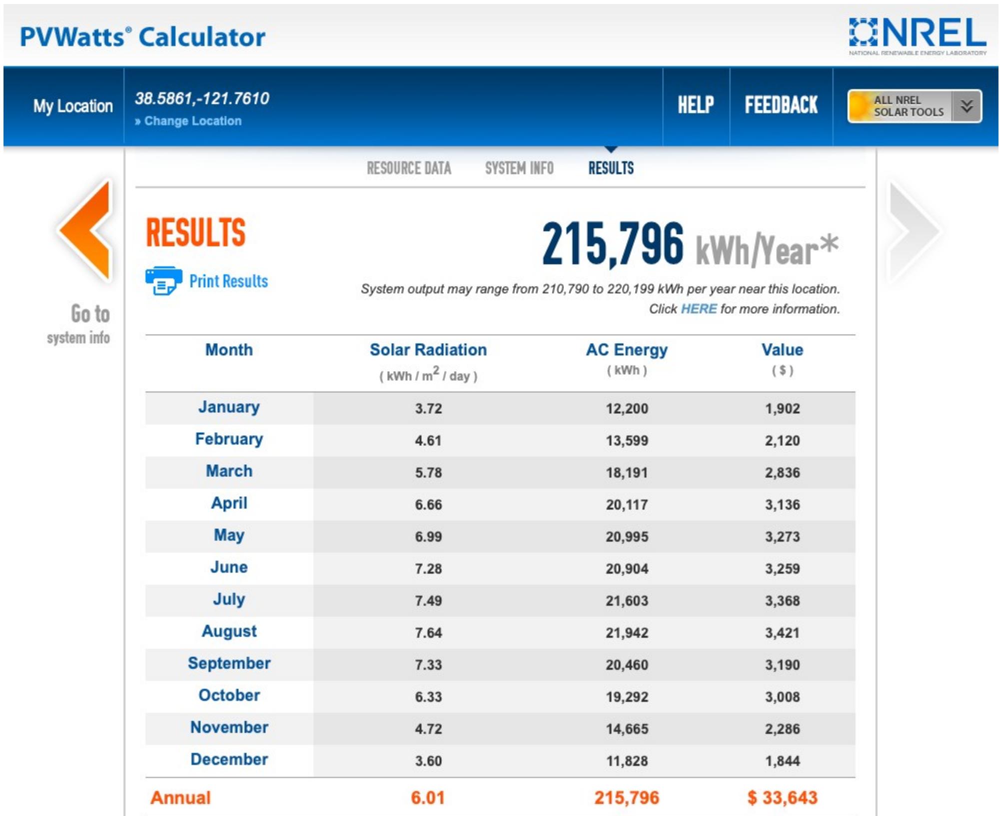
Latitude	Longitude	Average Daily Insolation (kWh/m²/day)	Assumptions
38.53	−121.78	6.01	38° tilt
38.53	−121.74	6.01	
38.69	−121.78	6.00	
38.69	−121.74	5.98	
38.53	−121.78	5.94	23° tilt

7.2.4 *Case Analysis—Part 3: Calculate the Size of the System*

In Section 7.2.2, the total load was tabulated to require 588 kWh/day or 215 MWh/year. The PVWatts simulation parameters are summarized in Table 7.8, using default values for all inputs except for the tilt, which was set to latitude tilt, and the size of the system, which was adjusted to give the specified MWh/year. The simulated electricity generation is shown in Figure 7.10, and visualization of the simulated output of a similar system is shown in Figure 7.11.

Table 7.8. Parameters/Results for PVWatts Simulation for the Second Case Study.

Parameter	Description	Value	Unit
Latitude		38.5861	Degrees
Longitude		−121.7610	Degrees
PV nameplate capacity	Nameplate capacity of the PV system.	133	kWdc
Inverter efficiency	Conversion efficiency from the inverter.	96	Percentage
DC-to-AC ratio	Ratio between DC (PV modules) capacity and AC (inverter) capacity.	1.2	Unitless
Tilt	System inclination relative to the horizontal.	38 (latitude tilt, rounded down)	Degrees
Azimuth angle	Orientation of the system. North = 0°, N-S = 180°.	180	Degrees
System losses	Simplified performance losses.	14.08	Percentage
Ground coverage ratio	Area of modules/area of total system.	0.4	Unitless
System size	Size of system selected.	2,217	m²
Module efficiency	Electricity generated relative to energy of light striking the module.	15	Percentage
Results: Annual energy	**Output of system described above.**	**216**	**MWh/y**



Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	3.72	12,200	1,902
February	4.61	13,599	2,120
March	5.78	18,191	2,836
April	6.66	20,117	3,136
May	6.99	20,995	3,273
June	7.28	20,904	3,259
July	7.49	21,603	3,368
August	7.64	21,942	3,421
September	7.33	20,460	3,190
October	6.33	19,292	3,008
November	4.72	14,665	2,286
December	3.60	11,828	1,844
Annual	6.01	215,796	$ 33,643

Figure 7.10. Results of PVWatts simulation for parameters in Table 7.8.

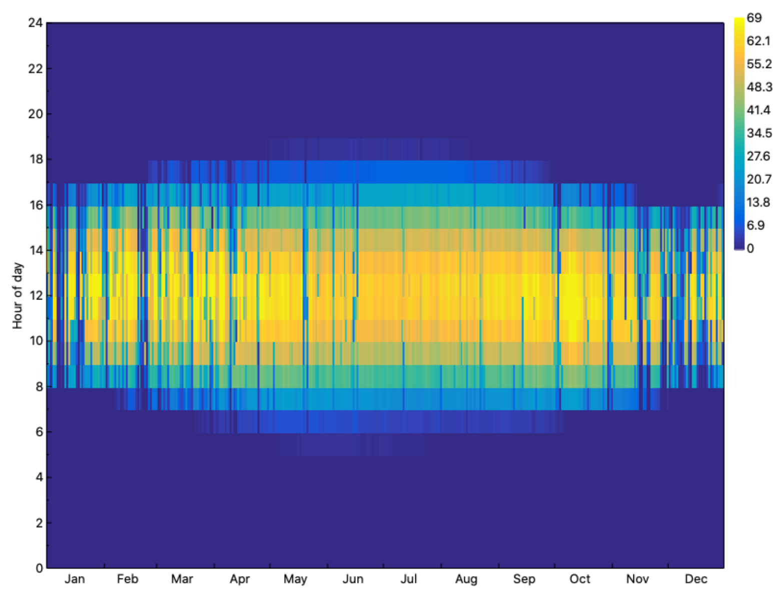


Figure 7.11. Visualization of simulated output of PV system at Case 2 location.

7.2.5 Case Analysis—Part 4: Siting the System

An area of 2200 m^2 is required for the array according to the simulation and the assumptions of a ground coverage ratio of 0.4 and a module efficiency of 15 percent, which is the PVWatts default setting. Today's modules have increased in efficiency, allowing this system to possibly fit in an area closer to 1750 m^2. Three locations were considered and documented to have ample space for a system of this size, as shown in Figure 7.12–7.14.

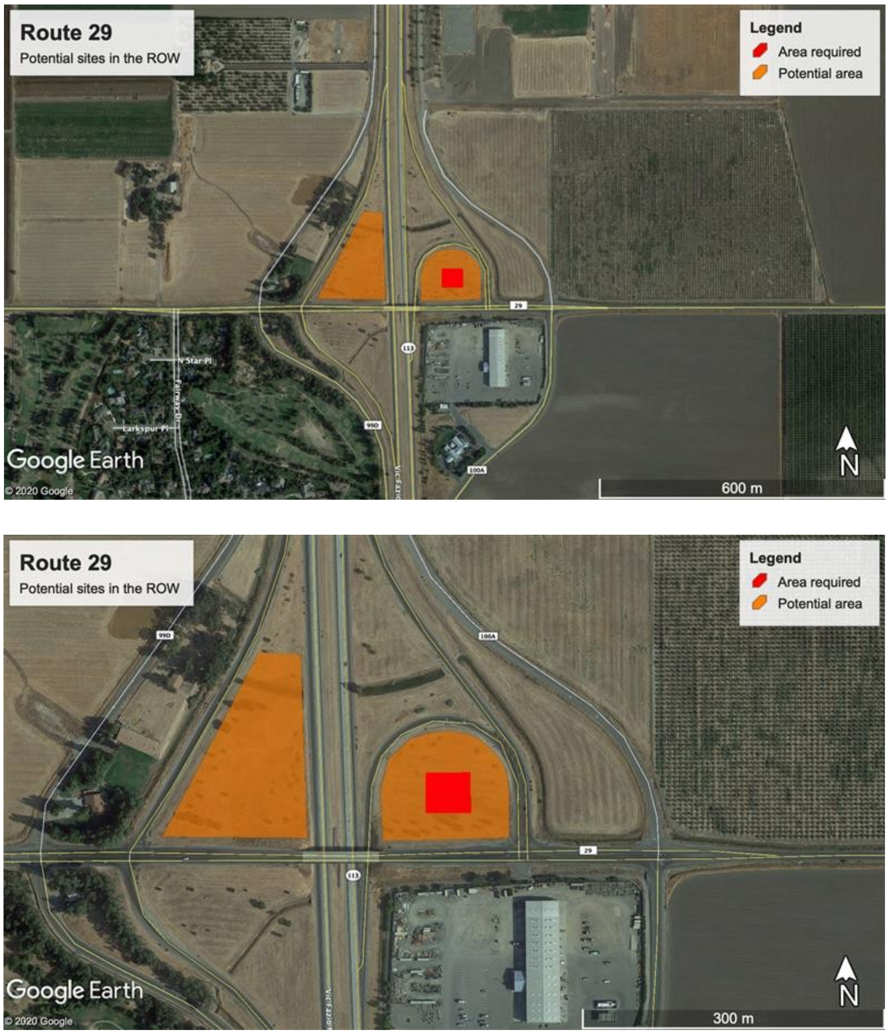


Figure 7.12. Road 29 potential site for Case 2.

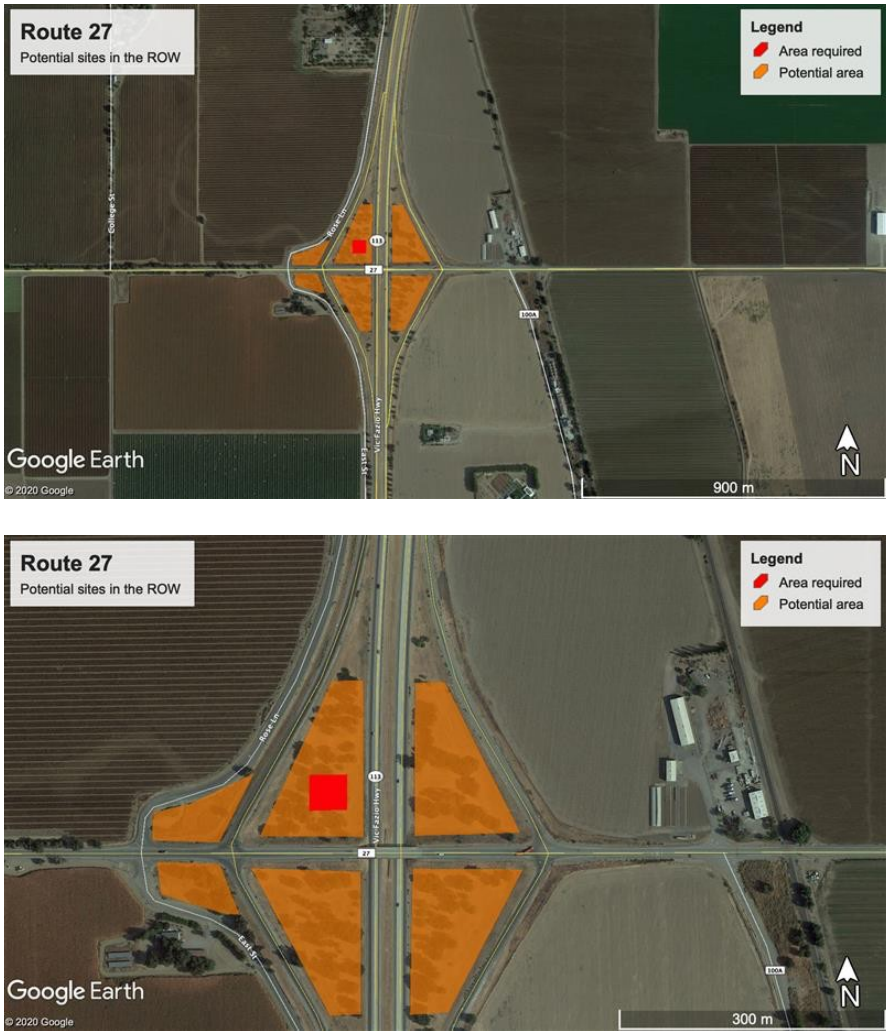


Figure 7.13. Road 27 potential site for Case 2.

The site suggested in Figure 7.14 may be considered unacceptable because of being a detention pond. However, one of the fastest growing segments of solar deployments currently is “floating PV” in which the solar modules float on a body of water. Dual use of land is always an attractive thing. If floating PV hardware may be adapted to be used in the detention pond there is some chance that this could be an innovative choice, but would require additional evaluation and design, increasing cost, so is unlikely to be the chosen location.

Figure 7.14. SR-113 and I-80 potential site for Case 2.

7.2.6 *Case Analysis—Part 5: Other Considerations*

The preceding sections focused on calculations related to the solar resource and system size discussed in Section 4.1. The considerations addressed in Section 4.2 are very relevant to this case but have not been included in this analysis. The considerations discussed in Section 4.3 are summarized in Table 7.9.

Table 7.9. Practical Considerations for Case 2.

Consideration	Comments
Safety and security	It appears that all of the sites are large enough that they could be secured with a fence, and the locations appear to be remote enough that special safety or security issues relative to those that occur for all solar plants are not anticipated.
Future plans	The two sites near SR-27 and SR-29 both appear to be approximately midway between Davis and Woodland, with the SR-27 site being slightly more remote. Both sites should not be affected by future growth over the next 25 years.
Site preparation	Based on the above images, most sites would be appropriate. However, the site shown in Figure 7.14 would need to be investigated because it appears to be a detention pond and might require special accommodations.
Maintenance	Vegetation will likely need to be periodically trimmed. Caltrans is in a good position to identify existing mowing operations that could be leveraged for this system.
Glint and glare	Glint and glare should be discussed in public meetings to assess concern. For these sites, any serious problem may be avoided by changing the orientation of the system.

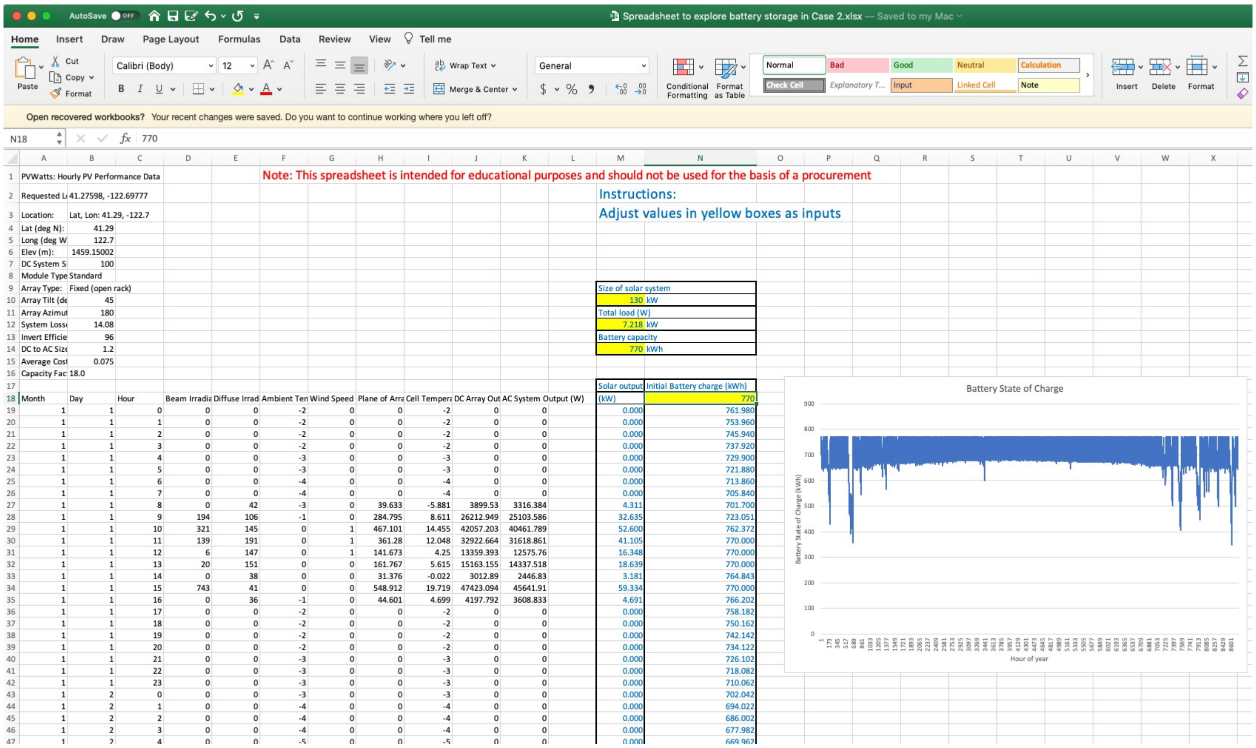
The final implementation of the project would use a more thorough analysis, especially including the economics of the net-metering arrangement, but it appears that the implementation of the Case 2 system could be done at any of two general locations using a system on the order of 130 kW and area around 2000 m^2. The system may use a fairly standard design. Adding between two and four hours of battery storage may be considered if doing so would improve the economics.

7.3 Case 2: Spreadsheet Demonstrating Calculation

The spreadsheet was created to allow the reader to understand how to estimate the performance of an off-grid system, especially within the context of sizing the battery to achieve the desired level of reliability. It should be used as an educational tool and not to size a system that will be purchased because the inputs are unlikely to reflect the actual performance of the selected hardware.

An image of the spreadsheet is shown in Figure 7.15. The data in Columns A through L are the downloaded file from PVWatts. A user should first download the PVWatts file relevant to the desired location and system orientation. Note that any system size may be assumed for the PVWatts calculation because the spreadsheet adjusts according to the value in B7.

Once the new spreadsheet is obtained, Columns M and N (as well as the graph) should be copied from the original spreadsheet (shown in Figure 7.15), confirming that the cells line up in the new PVWatts file to duplicate the alignment shown in Figure 7.15. The calculation is then completed by adjusting the values in the four yellow cells (M10, M12, M14, and N18). Cell M10 (size of solar system) will scale the output of the solar system, while M12 adjusts the constant load. The user may introduce a time-dependent load by adjusting the equations in Column N. The battery capacity is entered in cell M14. The equation in Column N prevents charge accumulating in the battery above this number. Finally, N18 is adjusted to reflect the starting charge. The user may consider doing the calculation and then taking the charge state at the end of December to use as the starting point for the charge on January 1.



PVWatts: Hourly PV Performance Data
Note: This spreadsheet is intended for educational purposes and should not be used for the basis of a procurement
Requested L 41.27598, -122.69777
Instructions:
Location: Lat, Lon: 41.29, -122.7
Adjust values in yellow boxes as inputs
Lat (deg N): 41.29
Long (deg W 122.7
Elev (m): 1459.15002
DC System S 100
Module Type Standard
Array Type: Fixed (open rack)
Array Tilt (de 45
Array Azimut 180
System Loss 14.08
Invert Efficie 96
DC to AC Size 1.2
Average Cost 0.075
Capacity Fac 18.0

Size of solar system: 130 kW
Total load (W): 7.218 kW
Battery capacity: 770 kWh

Month	Day	Hour	Beam Irradia	Diffuse Irrad	Ambient Ten	Wind Speed	Plane of Arra	Cell Tempera	DC Array Out	AC System Output (W)	Solar output (kW)	Initial Battery charge (kWh)
												770
1	1	0	0	0	-2	0	0	-2	0	0	0.000	761.980
1	1	1	0	0	-2	0	0	-2	0	0	0.000	753.960
1	1	2	0	0	-2	0	0	-2	0	0	0.000	745.940
1	1	3	0	0	-2	0	0	-2	0	0	0.000	737.920
1	1	4	0	0	-3	0	0	-3	0	0	0.000	729.900
1	1	5	0	0	-3	0	0	-3	0	0	0.000	721.880
1	1	6	0	0	-4	0	0	-4	0	0	0.000	713.860
1	1	7	0	0	-4	0	0	-4	0	0	0.000	705.840
1	1	8	0	42	-3	0	39.633	-5.881	3899.53	3316.384	4.311	701.700
1	1	9	194	106	-1	0	284.795	8.611	26212.949	25103.586	32.635	723.051
1	1	10	321	145	0	1	467.101	14.455	42057.203	40461.789	52.600	762.372
1	1	11	139	191	0	1	361.28	12.048	32922.664	31618.861	41.105	770.000
1	1	12	6	147	0	1	141.673	4.25	13359.393	12575.76	16.348	770.000
1	1	13	20	151	0	0	161.767	5.615	15163.155	14337.518	18.639	770.000
1	1	14	0	38	0	0	31.376	-0.022	3012.89	2446.83	3.181	764.843
1	1	15	743	41	0	0	548.912	19.719	47423.094	45641.91	59.334	770.000
1	1	16	0	36	-1	0	44.601	4.699	4197.792	3608.833	4.691	766.202
1	1	17	0	0	-2	0	0	-2	0	0	0.000	758.182
1	1	18	0	0	-2	0	0	-2	0	0	0.000	750.162
1	1	19	0	0	-2	0	0	-2	0	0	0.000	742.142
1	1	20	0	0	-2	0	0	-2	0	0	0.000	734.122
1	1	21	0	0	-3	0	0	-3	0	0	0.000	726.102
1	1	22	0	0	-3	0	0	-3	0	0	0.000	718.082
1	1	23	0	0	-3	0	0	-3	0	0	0.000	710.062
1	2	0	0	0	-3	0	0	-3	0	0	0.000	702.042
1	2	1	0	0	-4	0	0	-4	0	0	0.000	694.022
1	2	2	0	0	-4	0	0	-4	0	0	0.000	686.002
1	2	3	0	0	-4	0	0	-4	0	0	0.000	677.982
1	2	4	0	0	-5	0	0	-5	0	0	0.000	669.962

Figure 7.15. Image of spreadsheet described in Section 7.1 and used to create Figure 7.6 and 7.7.

APPENDIX A: STANDARDS ORGANIZATIONS FOR SOLAR

This appendix provides an overview of standards organizations that are contributing useful standards relevant to solar systems. The information may help to guide the understanding of the standards listed in Appendix B.

Organization	Description
ASTM: American Society for Testing and Materials	ASTM is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services. The ASTM standards are most commonly used for calibrating irradiance measuring devices.
IEC: International Electrotechnical Commission	IEC is the world's leading organization that prepares and publishes international standards for all electrical technologies. Millions of devices that contain electronics, and use or produce electricity, rely on IEC International Standards and Conformity Assessment Systems to perform, fit, and work safely together. IEC is a not-for-profit, quasi-governmental organization, founded in 1906. IEC cooperates with ISO to ensure that international standards fit together seamlessly and complement each other.
IECRE: IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications	IECRE was formed to partner with ISO in overseeing the implementation of IEC standards at the system level. Notably, the IECRE OD series 401, 402, 404 confirms design, testing performance requirements, installation, and other details that are critical to the quality of PV plant systems.
IEEE-SA: Institute of Electrical and Electronics Engineers Standards Association	IEEE is the world's largest professional association for the advancement of technology. IEEE-SA is a leading developer of international standards that underpin many of today's telecommunications, information technology, and power-generation products and services.
ISO: International Standards Organization	ISO certifications are designed to certify that a management system, manufacturing process, service, or documentation procedure has all the requirements for standardization and quality assurance. ISO is an independent, non-governmental, international organization that develops standards to ensure the quality, safety, and efficiency of products, services, and systems. ISO certifications exist in many areas of industry, from energy management and social responsibility to medical devices and energy management. ISO standards are in place to ensure consistency. Each certification has separate standards and criteria and is classified numerically. For instance, the ISO certification ISO 9001:2008 is widely used.
NFPA:	NFPA, a global not-for-profit organization established in 1896 that is devoted to eliminating death, injury, property, and economic

Organization	Description
National Fire Protection Agency	loss due to fire, electrical, and related hazards, has developed more than 300 consensus codes and standards. NFPA 1, Fire Code, advances fire and life safety for the general public and first responders in the United States by providing a comprehensive, integrated approach to a fire code regulation and hazard management. NFPA's work on solar is primarily focused on the hazards associated with solar systems attached to buildings.
SEMI: Formerly called Semiconductor Equipment and Materials International	The SEMI International Standards Program is one of the key services offered by SEMI for the benefit of the worldwide semiconductor, PV, LED, MEMS, and flat panel display industries. The program, started over 40 years ago in North America, was expanded in 1985 to include Europe and Japan, and now also has technical committees in China, Korea, and Taiwan. SEMI standards related to PV most commonly focus on material purity specifications and other details related to the solar cells themselves.
SunSpec Alliance	The SunSpec Alliance is an alliance of over 100 solar and storage distributed energy industry participants based in the San Francisco Bay Area. SunSpec standards address operational details of solar PV power and energy storage plants on the smart grid—including residential, commercial, and utility-scale systems—thus reducing cost, promoting technology innovation, and accelerating industry growth.
UL: Underwriters Laboratory	Underwriters Laboratories Inc. specializes in product safety. It helps customers, companies, and stakeholders navigate market complexity by providing inspection, advisory services, education and training, testing, auditing and analytics, certification software solutions, and marketing claim verification. Founded in 1894, UL develops over 1,500 standards used to test components, materials, systems, and performance, and to assess products. In the United States, UL is accredited by ANSI as an audited designator.

APPENDIX B: LIST OF STANDARDS

B.1 Standards Related to Solar Modules

IEC 60904-13:2018, *Photovoltaic Devices – Part 13: Electroluminescence of Photovoltaic Modules,* covers details applicable to PV modules measured with a power supply that places the cells in the modules in forward bias. This standard entails general methods for laboratory or production-line PV module electroluminescent imaging but not the specific details that are most relevant to outdoor imaging of operational power plants. For outdoor imaging, see IEC 62446-3. This standard provides methods to:

- Capture electroluminescence images of photovoltaic modules.
- Process images to obtain metrics about the images taken in quantitative terms.
- Provide guidance to qualitatively interpret the images for features in the image that are observed.

IEC 61215-1:2016, *Terrestrial Photovoltaic (PV) Modules – Design Qualification and Type Approval – Part 1: Test Requirements,* provides up-to-date test requirements for design qualification and type approval of terrestrial PV modules capable to serve long-term operation in general open-air climates, found in Part 2 of IEC 60721-2-3:2013. Particularly, this standard is intended to apply to all terrestrial flat-plate module materials, such as crystalline silicon module types as well as thin-film modules. The objective of this test sequence is to determine the electrical and thermal characteristics of the module and to show, within reasonable constraint guidelines of cost and time, that the module is capable of withstanding prolonged exposure in open-air climates. The actual life expectancy of PV modules will depend on their design, their environment, and the conditions under which they are operated. Part 1 lists general requirements, Part 1-x provides specifics for each PV technology, and Part 2 defines testing. All tests defined in Part 2 are module-quality tests.

IEC 61215-1-1:2016, *Terrestrial Photovoltaic (PV) Modules – Design Qualification and Type Approval – Part 1-1: Special Requirements for Testing of Crystalline Silicon Photovoltaic (PV) Modules,* provides requirements specific to crystalline silicon modules, such as testing for the effects of light-induced degradation.

IEC 61215-1-2:2016, *Terrestrial Photovoltaic (PV) Modules – Design Qualification and Type Approval – Part 1-2: Special Requirements for Testing Thin-Film Cadmium Telluride (CdTe) Based Photovoltaic (PV) Modules*, provides requirements specific to thin-film CdTe modules, such as testing for transient performance behavior.

IEC 61215-1-4:2016, *Terrestrial Photovoltaic (PV) Modules – Design Qualification and Type Approval – Part 1-4: Special Requirements for Testing of Thin-Film $Cu(In,Ga)(S,Se)_2$ Based Photovoltaic (PV) Modules,* provides requirements specific to all thin-film $Cu(In,Ga)(S,Se)_2$ modules, such as testing for transient performance behavior.

IEC 61215-2:2016, *Terrestrial Photovoltaic (PV) Modules – Design Qualification and Type Approval – Part 2: Test Procedures,* applies test procedures in all technological devices related to all terrestrial flat-plate module materials, such as crystalline silicon module types as well as thin-film modules. This standard refers to special requirements of module testing and electrical and thermal operations under specific environmental conditions from Part 1. The actual life expectancy of modules will depend on their design, their environment, and the conditions under which they are operated.

IEC 61730-1:2016, *Photovoltaic (PV) Module Safety Qualification – Part 1: Requirements for Construction,* specifies and describes the fundamental construction requirements for PV modules in order to provide safe electrical and mechanical operation. Specific topics are provided to assess the prevention of electrical shock, fire hazards, and personal injury due to mechanical and environmental stresses. This part of IEC 61730 pertains to the particular requirements of construction. IEC 61730 Part 2 defines the requirements of testing. This international standard series lays down IEC requirements of terrestrial photovoltaic modules suitable for long-term operation in open-air climates. This standard is intended to apply to all terrestrial flat-plate module materials, such as crystalline silicon module types as well as thin-film modules. PV modules in this standard are set at a limit of a maximum DC system operating voltage of 1500 V.

IEC 61730-2:2016 RLV, *Photovoltaic (PV) Module Safety Qualification – Part 2: Requirements for Testing,* provides the testing sequence intended to verify the safety of PV modules whose construction has been assessed in IEC 61730-1. The test sequence and pass criteria are designed to detect the potential breakdown of internal and external components of PV modules that would result in fire, electric shock, and/or personal injury. The standard defines the basic safety test requirements and additional tests that are a function of the PV module end-use applications. Test categories include general inspection, electrical shock hazard, fire hazard, mechanical stress, and environmental stress.

UL 61730-1 and UL 61730-2 (replaces UL 1703:2018), *Photovoltaic (PV) Module Safety Qualification,* is the U.S. version of IEC 61730, with national differences to cover the requirements and electrical connective components for flat-plate PV modules for activities of installation on buildings and mounting facilities, such as integral and freestanding methods. These requirements are in accordance with the NEC, NFPA 70, and model building codes. Modules are tested for use in a system with operating voltage up to 1500 V.

IEC 62941:2019, *Terrestrial Photovoltaic (PV) Modules – Quality System for PV Module Manufacturing*, is applicable to organizations manufacturing PV modules certified to IEC 61215 series for design qualification and type approval and IEC 61730 for safety qualification and type approval. The design qualification and type approval of PV modules depend on appropriate methods for product and process design, as well as appropriate control of materials and processes used to manufacture the product. This document lays out best practices for product design, manufacturing processes, and selection and control of materials used in the manufacture of PV modules that have met the requirements of IEC 61215 series and IEC 61730. These standards also form the basis for factory audit criteria of manufacturing sites by various certifying and auditory bodies.

The object of this document is to provide a framework for the improved confidence in the ongoing consistency of performance and reliability of certified PV modules. The requirements of this document are defined with the assumption that the quality management system of the organization has already fulfilled the requirements of ISO 9001 or equivalent quality management system. This document is not intended to replace or remove any requirements of ISO 9001 or equivalent quality management system. By maintaining a manufacturing system in accordance with this document, PV modules are expected to maintain their performance as determined from the test sequences in IEC 61215 series and IEC 61730.

IEC TS 63126, *Guidelines for Qualifying PV Modules, Components and Materials for Operation at High Temperatures*, defines additional testing requirements for modules deployed under conditions leading to higher module temperature that are beyond the scope of IEC 61215-1 and IEC 61730-1 and the relevant component standards, IEC 62790 and IEC 62852. The testing conditions specified in IEC 61215-2 and IEC 61730-2 (and the relevant component standards IEC 62790 and IEC 62852) assumed that these standards are applicable for module deployment where the 98th percentile temperature—that is, the temperature that a module would be expected to equal or exceed for 175.2 h per year—is less than 70°C.

IEC TS 63209 ED1, *Extended-Stress Testing of Photovoltaic Modules for Risk Analysis*, is not yet in print but is intended to provide a standardized method for evaluating longer-term reliability of PV modules and for different bills of materials for the same model than is provided with the baseline testing defined in IEC 61215, which is a qualification test with pass-fail criteria. The included test sequences in this specification are intended to provide information for comparative qualitative analysis using stresses relevant to application exposures to target known failure modes.

IECRE OD-405-1, *IECRE Operational Document 405-1 – IECRE Certified Equipment Scheme – IECRE Quality System Requirements for PV Module Manufacturers – Part 1: Requirements for Certification of a Quality System for PV Module Manufacturing*, specifies particular requirements and guidance on the establishment and maintenance of a quality system to meet the requirements of the IECRE scheme. It does not preclude the use of other quality systems that are compatible with the objectives of ISO 9001:2015, subject to the acceptance of a renewable energy certification body (RECB). Therefore, when RECBs assess the quality management systems of manufacturers, this document should be the basis of the initial assessment and subsequent surveillance visits.

IECRE OD-405-2, *IECRE Quality System Requirements for PV Module Manufacturers – Part 2: Audit Checklist*, provides an audit checklist to address questions, verify, and define whether a system is within working limits. Use of this checklist facilitates consistent implementation of IEC 62941.

IECRE OD-405-3, *IECRE Quality System Requirements for PV Module Manufacturers – Part 3: Requirements for PV Factory Auditors*, defines requirements for various grades of PV factory auditors who conduct audits of PV module manufacturers' quality management systems. These requirements are designed to enable completion of these audits in a uniform manner. An application form for the factory auditor is included. The IECRE system provides for the audit and surveillance of PV module manufacturers' quality management systems in accordance with IEC/TS 62941.

IECRE OD-406-1, *PV-OMC IECRE Certification Body (RECB) and IECRE Inspection Body (REIB) Application Form*, is completed by the candidate RECB or REIB and is submitted by the member body in which the candidate resides. The member body ensures that the application package is complete.

B.2 Standards Related to Solar Systems

IEC 61724-1:2017, *Photovoltaic System Performance – Part 1: Monitoring*, outlines equipment, methods, and terminology for performance monitoring and analysis of PV systems. This documentation provides three classifications of monitoring a system to reflect the accuracy (and cost) of the monitoring. It addresses sensors, installation, and accuracy for monitoring equipment in addition to measured parameter data acquisition and quality checks, calculated parameters, and performance metrics. This serves as a basis for other standards that rely upon the data collected.

IEC 62446-1:2016+AMD1:2018 CSV, *Photovoltaic (PV) Systems – Requirements for Testing, Documentation, and Maintenance – Part 1: Grid Connected Systems – Documentation, Commissioning Tests and Inspection*, defines the information and documentation required to be handed over to a customer following the installation of a grid-connected PV system. It also describes the commissioning tests, inspection criteria, and documentation expected to verify the safe installation and correct operation of the system. This part of IEC 62446 is written for grid-connected PV systems that do not utilize energy storage (e.g., batteries) or hybrid systems. Significantly, this is for use by installation contractors of grid-connected solar PV systems as a template to provide effective documentation to a customer after installation and for subsequent reinspection, maintenance, or modifications.

IEC 62548:2016, *Photovoltaic (PV) Arrays – Design Requirements,* sets out design requirements for PV arrays including DC array wiring, electrical protection devices, switching, and earthing provisions. The scope includes all parts of the PV array up to but not including energy storage devices, power-conversion equipment (PCE), or loads. An exception is that provisions relating to PCE are covered only where DC safety issues are involved. The interconnection of small DC conditioning units intended for connection to PV modules is also included. The object of this document is to address the design safety requirements arising from the particular characteristics of PV systems. Direct current systems, and PV arrays in particular, pose some hazards in addition to those derived from conventional AC power systems, including the ability to produce and sustain electrical arcs with currents that are not greater than normal operating currents. In grid-connected systems, the safety requirements of this document are, however, critically dependent on the inverters associated with PV arrays complying with the requirements of IEC 62109-1 and IEC 62109-2. In this part of the standard, there are also extra protection requirements of PV arrays when they are directly connected with batteries at the DC level.

IEC 63157:2019, *Photovoltaic Systems – Guidelines for Effective Quality Assurance of Power Conversion Equipment*, lays out recommendations for best practices for product realization, safety, customer satisfaction, and stakeholders' relationship used in the manufacture of PCE. It captures key requirements customers would like to see completed to ensure high-quality products, specifically, that the products have the documented properties, including properties needed to give customer satisfaction with regard to the warranty. The object of this document is to provide more confidence in the ongoing consistency of performance and reliability of certified PCE. The requirements of this document are defined with the assumption that the quality management system of the organization has already fulfilled the requirements of ISO 9001 or equivalent quality management system. These guidelines also form the basis for factory audit criteria of such sites by various certifying and auditory bodies. This document covers manufacture of electronic PCE intended for use in terrestrial PV applications. The term PCE refers to equipment and components for electronic power conversion of electric power into another kind of electric power with respect to voltage, current, and frequency. This document applies to PCE in both indoor and outdoor open-air climates as defined in IEC 60721-2-1 and IEC 60721-3-3. Such equipment may include, but is not limited to, DC-to-AC inverters, DC-to-DC converters, and battery charge converters.

IECRE OD-401:2020, *Conditional PV Plant Certificate*, defines the requirements for issuance of a conditional PV plant certificate that covers the electrical, mechanical, and civil work of the PV plant based on conformance assessment to the relevant IEC and other international standards to ensure if they are installed and functioning as designed. It gives oversight of the design and manufacture of the components as well as the design, installation, and operation of a PV system. A conditional PV project certificate may be completed at the time a PV system is commissioned. The annual PV project certificate from OD-402 builds on the conditional PV project certificate by documenting a full year of operation and associated maintenance.

IECRE OD-402:2016, *Annual PV Plant Performance Certificate*, defines the requirements for issuance of an annual PV plant performance certificate that reflects the ongoing performance of the system. This certificate refers to specific details of OD-401 in providing information about the design, quality control during installation, and initial performance. The objective of this certificate documents electrical energy delivered relative to what would be expected for measured weather. There are two categories of losses in output depending on the system's functionality. The annual PV plant performance certificate reports performance data from a full year of operation as well as the maintenance costs to achieve stated performance and availability. This certification may be issued annually to reflect the ongoing health of the PV system.

IECRE OD-404:2018, *PV Plant Operational Status Assessment*, defines the requirements for a PV plant operational status assessment report that reflects the past performance, current condition, and anticipated future performance of a PV plant based on an assessment that includes:

- Prior completion of OD-402 Annual PV Plant Performance Certificate and OD-410 Quality System Requirements for PV Plant Installation and Maintenance.
- Review of maintenance records using IEC 62446-2.
- Plant inspection using IEC 62446-1, IEC TS 62446-3, and IEC TS 60904-13 or similar.

In addition, the assessment includes historical plant documentation (such as as-built documentation, weather and plant performance data, and O&M plan for the future). The assessment may be applied to any PV plant using Class A, B, or C accuracy, as defined in IEC 61724-1 for the performance assessments.

IECRE OD-410-1, *IECRE Quality System Requirements for PV Plant Installation and Maintenance – Part 1: Requirements for Certification*, specifies particular requirements and guidance on the establishment and maintenance of a quality system (not the individual implementations—the audit is of the organization, not of each site) to meet the requirements of the IECRE scheme. It does not preclude the use of other quality systems that are compatible with the objectives of ISO

9001 subject to the acceptance of an RECB. Therefore, when RECBs assess the quality systems of installation contractors and O&M providers, this document should be the basis of the initial assessment and subsequent surveillance visits.

IEC TS 61724-2:2016, *Photovoltaic System Performance – Part 2: Capacity Evaluation Method*, defines a non-regression-based method for measuring and analyzing the power output production of a specific PV system with the goal of evaluating the quality of the PV system performance. The test is intended to be applied during a relatively short time period (a few relatively sunny days) in initial reference to the complete PV plant performance details in Part 3 of IEC 61724. The performance of the system is quantified both during times when the inverters are maximum-power-point tracking and during times when the system power is limited by the output capability of the inverter or interconnection limit, reducing the system output relative to what it would have been with an inverter with generation freely following irradiance, if this condition is relevant. The intent of this document is to specify a procedure for comparing the measured and actual power output produced against the expected power from the PV system on relatively sunny days based on its design parameters.

IEC TS 61724-3:2016, *Photovoltaic System Performance – Part 3: Energy Evaluation Method*, defines a procedure for measuring and analyzing the energy production of a specific PV system relative to expected electrical energy production for the same system from actual weather conditions as defined by the stakeholders of the test. The energy production is characterized specifically for times when the system is operating (available); times when the system is not operating (unavailable) are quantified as part of an availability metric. The aim of this technical specification is to define a procedure for comparing the measured electrical energy with the expected electrical energy of the PV system.

IEC TS 62446-3:2017, *Photovoltaic (PV) Systems – Requirements for Testing, Documentation and Maintenance – Part 3: Photovoltaic Modules and Plants – Outdoor Infrared Thermography,* defines outdoor thermography on PV modules and BOS components using passive techniques for power plants in operation, under natural light—without external power or irradiation sources. This inspection supports the preventive maintenance for fire protection, the availability of the system for power production, and the inspection of the quality of the PV modules. This document lays down requirements for the measurement equipment, ambient conditions, inspection procedure, inspection report, and personnel qualifications, and provides a matrix for thermal abnormalities, as a guideline for the inspection.

IEC TS 63049:2017, *Terrestrial Photovoltaic (PV) Systems – Guidelines for Effective Quality Assurance in PV Systems Installation, Operation and Maintenance*, implements an effective quality assurance program for the managing and reducing of risk in the installation and operation of PV systems. This document defines requirements for certifying that an entity has and uses a quality assurance program to prevent or reduce errors and learns from any new errors in installation, operation, and maintenance of all PV systems. The objective of this document is to provide more confidence in the performance, quality control, and reliability of certified PV systems and nonconventional flat-plate systems. By being installed and operated under a quality assurance program in accordance with this document, PV systems are expected to operate as designed and as expected based on product warranties.

IEEE 1547, *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems*, is a series of interconnection standards overseeing connection of electric power systems to the grid. Traditionally, utility electric power systems (EPSs—grid or utility grid) were not designed to accommodate active generation and storage at the distribution level. As a result, there are major issues and obstacles to an orderly transition to using and integrating distributed power resources with the grid. The lack of uniform national interconnection standards and tests for interconnection operation and certification, as well as the lack of uniform national building, electrical, and safety codes, are understood. IEEE Std 1547 has the potential to be used in federal legislation and rulemaking and state public utilities commission deliberations, and by over 3000 utilities in formulating technical requirements for interconnection agreements for distributed generators powering the electric grid. It focuses on the technical specifications for, and testing of, the interconnection itself. It provides requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the interconnection. It includes general requirements, response to abnormal conditions, power quality, islanding, and test specifications and requirements for design, production, installation evaluation, commissioning, and periodic tests. The stated requirements are universally needed for interconnection of distributed resources, including synchronous machines, induction machines, or power inverters/converters, and will be sufficient for most installations.

IEEE 519:2014, *IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems*, elaborates on the specifics for the design of electrical systems that include both linear and nonlinear loads and describes harmonic controls in electrical power system devices. The voltage and current waveforms that may exist throughout the system are described, and waveform distortion goals for the system designer are established. The interface between sources and loads is described as the point of common coupling, and observance of the design goals will reduce interference between electrical equipment. This recommended practice addresses steady-state limitations. Transient conditions exceeding these limitations may be encountered. This document sets the quality of power that is to be provided at the point of common coupling.

ISO 9001:2015, *Quality Management Systems – Requirements*, specifies requirements for a quality management system when an organization:

- Needs to demonstrate its ability to consistently provide products and services that meet customer and applicable statutory and regulatory requirements.
- Aims to enhance customer satisfaction through the effective application of the system, including processes for improvement of the system and assurance of conformity to customer and applicable statutory and regulatory requirements.

All the requirements of ISO 9001:2015 are generic and are intended to be applicable to any organization, regardless of its type or size, or the products and services it provides. IEC 62941 and IEC 63157 are designed to complement ISO 9001 by giving technical details specific to PV modules and PCE, respectively.

NFPA 70, *National Electric Code*, aims to provide safe electrical design, installation, and inspection to protect people and property from electrical hazards. It covers the installation and removal of electrical conductors, equipment, and raceways; signaling and communications conductors, equipment, and raceways; and optical fiber cables and raceways for most public and private premises and buildings. This code does not cover automotive vehicles, communications equipment, and certain installations that fall under exclusive control by land or water with the exception of mobile homes or recreational vehicles.

UL 1741: 2010, *Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources*, sets safety requirements for PCE such as inverters. These requirements cover inverters, converters, charge controllers, and interconnection system equipment (ISE) intended for use in power systems. Utility-interactive inverters, converters, and ISE are intended to be operated in parallel with an EPS to supply power to common loads. For utility-interactive equipment, these requirements are intended to supplement and be used in conjunction with the *Standard for Interconnecting Distributed Resources with Electric Power Systems*, IEEE 1547, and the *Standard for Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems*, IEEE 1547.1. This standard has not been updated since 2010. Efforts are ongoing to harmonize it with IEC 62109.

UL 1998:2013, *1998 Standard for Software in Programmable Components*, is a reference standard in which the requirements are to be applied when specifically referenced by other standards or product safety requirements. These requirements are intended to address risks that occur in the software or in the process used to develop and maintain the software, such as the following:

- Requirement conversion faults that cause differences between the specification for the programmable component and the software design.
- Design faults such as incorrect software algorithms or interfaces.
- Coding faults, including syntax, incorrect signs, endless loops, and other coding faults.
- Timing faults that cause program execution to occur prematurely or late.
- Microelectronic memory faults, such as memory failure, not enough memory, or memory overlap.
- Induced faults caused by microelectronic hardware failure.
- Latent, user, input/output, range, and other faults that are only detectable when a given state occurs.
- Failure of the programmable component to perform any function at all.

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