Where Renewable Energy Meets the Building Envelope—the Building Science Aspects of Photovoltaic Integration With Roof Systems

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Abstract

With the dramatic growth of the photovoltaic (PV) systems industry during the past decade, roof assemblies have become a key component in the drive toward renewable-energy production. Although this has led to exciting new opportunities for roofing contractors and installers to add substantial new value to their offerings, it also has led to numerous unexpected challenges and adverse effects, including deficient roof integration leading to building envelope failures (e.g., air and/or water infiltration); reduction in service life of a roof system; inadequate structural and wind loading assessment; and effects of flame spread. Given the PV industry's sudden growth, many of these issues can be traced to not adopting clear and enforceable industry standard practices for this application, which would provide a baseline for a more robust, safe and effective integration between PV equipment and a roof assembly. However, the standardization process is catching up, with several new standard practices being developed by industry associations. This study evaluates the key building science considerations of PV roof integration through a detailed assessment of the critical structural components and

interfaces along with a survey of standardized material and test requirements that exist for PV systems' integration in various roof assemblies.

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Introduction

The explosive growth of roof-mounted PV systems is an exciting development in support of widespread use of renewable-energy generation. This trend also offers intriguing opportunities for professional roofing contractors to enhance the value of their offerings with specialized capability to integrate the renewable-energy power generation with the building envelope. However, this needs to be done with great care to prevent adverse performance effects for the building envelope, which can include moisture damage, service life reduction and structural and/or flame spread performance concerns. Given that installation of roof-mounted PV systems commonly is performed by specialized PV installers and no widely accepted standard procedures are in place, the quality and robustness of installations varies widely with a defining lack of uniformity to ensure installations meet minimum performance requirements. Although PV installers feature expertise in the design, sizing and home/grid connectivity of the installation, they typically are not experts regarding roof integration and maintaining the integrity of building envelopes. Many installation features can have unexpected adverse effects and tradeoffs on building envelopes and/or roof performance, which typically are not stated clearly in PV installation practices and guidelines. Some of these key tradeoffs are summarized in Table 1. To better understand the true effects of these tradeoffs, the PV and roofing industries need clear guidance and performance specification through an industry consensus standardization process.

TABLE 1: Key Tradeoffs for Various Photovoltaic (PV) System Installation Features

Installation Features	Benefit to PV Module	Potential Adverse Effects on Roof System
Mechanical fasteners to secure PV array	Meets structural and wind-load requirements	Moisture intrusion, damage to structural members
Installation of metal flashing components under roof shingles and tiles	Protects against water intrusion through roof fasteners; integrates with shingling of roof system	Damage caused to existing roof shingles/tiles? Effects on service life and warranty of roof?
Ballasted PV system on low-slope roof system	Meets structural and wind-load requirements; minimal roof penetrations	Structural degradation/ abrasion of roof surface / sagging, resulting in roof damage and/or water ponding
Adhered PV system to secure to low-slope roof system	Meets structural and wind-load requirements; minimal roof penetrations	Uncertain service life of adhesive system; reduced roof membrane service life?
High offset gap (greater than 5 inches) between array mounting structure and the roof system	Sufficient ventilation to limit module temperature rise, beneficial to module electrical output; enhanced access for roof maintenance and drainage of debris	Increased structural and wind-uplift requirements; air channeling effects on flame spread rating?
Low offset gap (less than 2 inches) between array mounting structure and the roof system	Enhanced aesthetics (building integrated), less effect of flame spread (adverse effects on module efficiency)	Thermal effect–higher temperature exposure may reduce service life of roofing materials and PV module
Lightweight/composite array racking/module framing system	Reduced structural loads, snap-fit design can reduce installation time and labor	Service life and durability of composite system; combustibility effects / wind load issues?

Several industry standards have been published or are being developed that specify material and physical requirements for roof-mounted PV system installations. The International Code Council Evaluation Service (ICC-ES) has published AC365, Acceptance Criteria for Building-Integrated Photovoltaic (BIPV) Roof Panels, which defines fire classification, wind resistance and durability requirements for these specialty products. In addition, the ICC-ES has proposed AC428, Proposed Acceptance Criteria for Modular Framing Systems Used to Support Photovoltaic (PV) Modules, which details structural requirements for wind, load and seismic exposures, as well as dead and live loads, for flush-mounted and free-standing PV systems. An excellent overview of structural loading calculation details is given by Yun Lee in "Pitched-Roof PV Mounting: Design and Engineering Considerations," February/March 2010 issue of *SolarPro* (solarprofessional.com). More general PV installation guidelines were developed in 2001 for the California Energy Commission through the publication of *A Guide to Photovoltaic (PV) System Design and Installation*. The National Electric Contractors Association (NECA) has drafted the NECA 412 "Standard for Installing Photovoltaic Power Systems," which addresses electrical connectivity and safety concerns for PV systems. A wide-ranging general review of PV installation and roof system enhancement recommendations from a roofing perspective is provided by the National Roofing Contractors Association's (NRCA's) *Guidelines for Roof-mounted Photovoltaic System Installations*, as well as Solar Energy International's (SEI's) *Photovoltaics: Design and Installation Manual*.

However, these documents do not fully address the building science implications of roof-mounted PV system installations on various roof systems, with specific focus on the individual structural components and interfaces that will affect the building envelope's integrity. The ASTM E44.09 standardization committee for Photovoltaic Electric Power Conversion is attempting to address this through draft work item WK#21327, "Standard Practice for the Attachment of Roof Mounted Photovoltaic Arrays on Steep-slope Roofs." This task group attempts to integrate expertise from the PV and roofing industry to address building integration from an interfacial/structural component approach. This study will expand on these effects, providing approaches for evaluation of the resulting effect on the building envelope and roof system.

Discussion

As previously mentioned, structural load requirements (considering wind, snow and seismic effects) for PV system installations into roof systems have been specified from numerous sources. Separate accounts have considered electrical connectivity and safety concerns. But the study of the holistic building science effect of integrating a renewable-energy electric power generation plant into a roof system has not been fully appreciated. The implications on roof service life, warranty, moisture resistance, thermal performance, combustability and numerous other effects brought into the context of specific PV array design and components, as well as specific installation practices, are needed to fully understand the building science effect. In support of this, an understanding of the role and function of the building envelope is necessary.

The Building Envelope

The building envelope serves as the outer shell of a building to protect the indoor environment from outdoor exposure, forming a durable separation of the interior and exterior climates. The building envelope design is a specialized melding of architectural and engineering practices to ensure the comfort, appearance, durability and efficiency of an occupied structure. Any penetration or breach of the building envelope’s protective shell, whether in the wall system via a window or door or in the roof through pipes, vents, skylights or PV arrays, must be carefully designed, tested and installed appropriately.

The consequences of building envelope penetrations of any kind that are not carefully designed, tested and installed appropriately is almost certain failure to some or all aspects of the building envelope, which can lead to permanent building damage. In the case of the fast-growing roof-mounted PV systems, the risk for adverse building envelope effect is high because of the lack of training with standardized practices—not to mention lack of definition in the building code—in the current state of the industry. This paper is intended to present a survey of the potential building envelope effects, using an individual structural component and interfacial approach.

The Critical Structural Components and Interfaces

Although much has been done in assessing structural requirements for a PV installation, these design considerations generally look at the installation as a whole rather than providing specific requirements for the individual structural components and interfaces. Because any link in the installation that is deficient in structural integrity, durability or installation details can result in failure of the entire PV system, it is prudent to evaluate individual critical structural components and interfaces as defined in the following assessment. These critical elements in this assessment include:

- Structural Component 1: Roof Structure
- Interface 1: Array Mounting Structure to the Roof Structure
- Structural Component 2: Array Mounting Structure
- Interface 2: Module Framing System to Array Mounting Structure
- Structural Component 3: Module Framing System

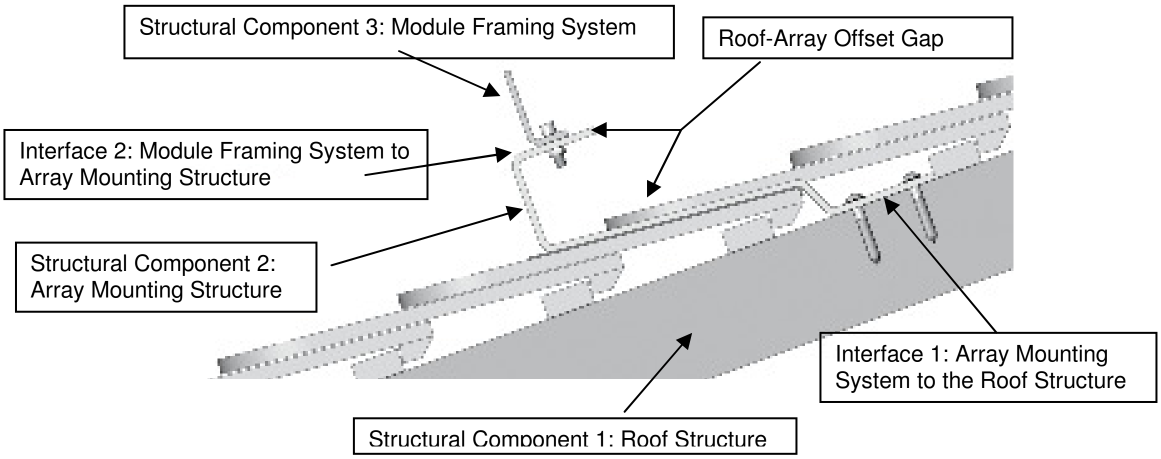

Figure 1: The critical structural components and interfaces for PV roof integration

Figure 1 provides a representative illustration (taken from ASTM E44.09 WK#21327) of a detail of a PV array's installation into a tile roof structure, with the critical structural components and interfaces identified. These components and interfaces could apply to many PV installations, whether steep- or low-slope, mechanically fastened, ballasted or adhered; however, the specific concerns and requirements for the structural components and interfaces will be dramatically different. As such, an individual assessment of the critical structural components and interfaces—in the order they typically are addressed during the field installation—is as follows.

Critical Structural Component 1: The Roof System

Roof Structural Load Requirements: The roof system is a critical component of the building envelope that protects the building and occupants from exterior environmental exposure. The components for a steep slope roof system include a roof deck material that covers the structural roof members (rafters), underlayment that protects the deck material and roof coverings (tiles, shingles, membrane, etc.) that provide the primary water-shedding and environmental protection to the roof system and building interior. Roof insulation can be integrated either above or below the deck depending on the roof system design. The components for a low-slope roof system also include a roof deck material, insulation that may include a vapor barrier, and a roof covering, typically in the form of a membrane, to provide the primary environmental protection to the roof system and building interior. For both low-slope and steep-slope designs, both “live loads”, such as wind exposure, and “dead loads,” such as snow, seismic, and objects applied to the roof, need to be carefully considered for roof structural load requirements. For illustration purposes, more details on the structural design requirements from wind loads is as follows.

The roof system’s wind load requirements are derived from regional wind exposures—as shown in Figure 2 for the U.S.—and can vary greatly depending on location, particularly in coastal regions.

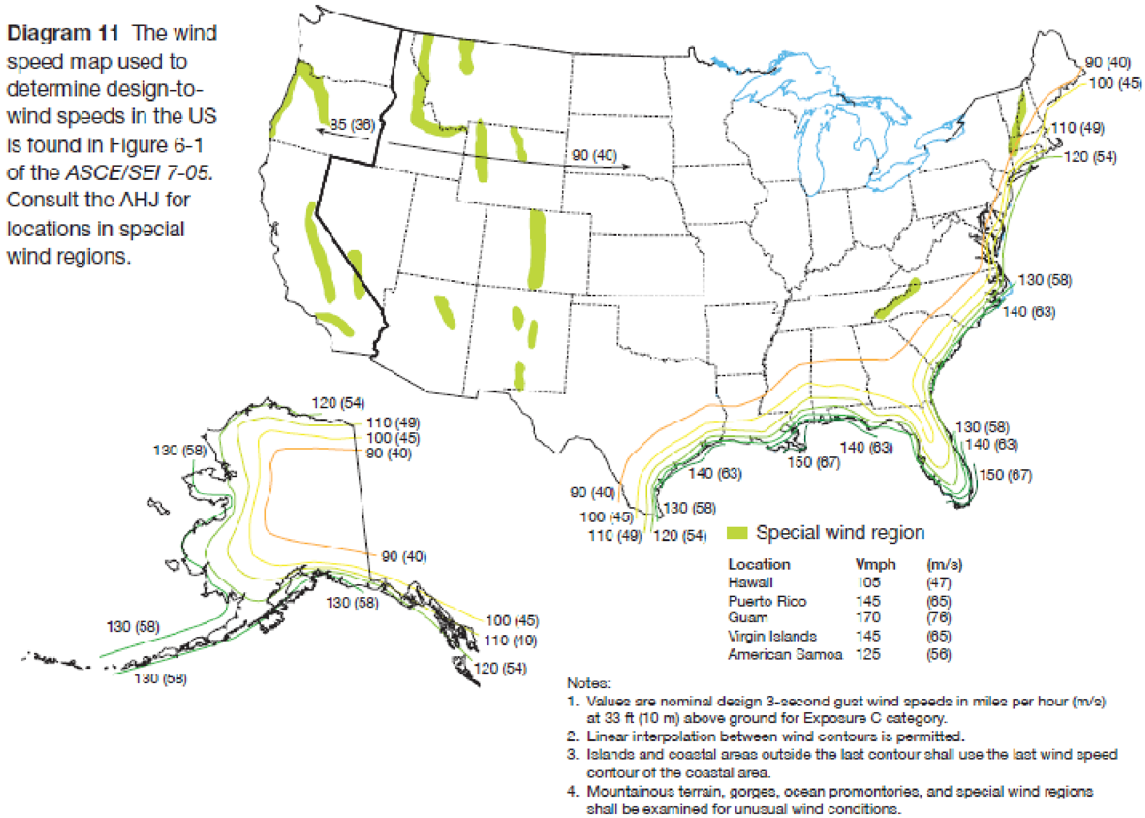

Figure 2: Wind speed map as presented in Figure 6-1 of the ASCE/SEI 7-05 (diagram taken from Yun Lee, "Pitched-Roof PV Mounting: Design and Engineering Considerations," February/March 2010, *SolarPro*, Diagram 11)

In addition to the wind-load requirements, the geometric roof design has significant effects on localized structural requirements. As detailed in Figure 3 for various roof shapes and configurations, there are localized "pressure zones" with increased load requirements at and near areas of pressure concentration on the roof. To be sure, these structural design considerations apply to a PV system's installation onto a roof, as well as the roof structure. In addition, snow, seismic and other "dead" loads must be considered for the total design load of a PV roof system. An excellent guide through these calculations is given by Yun Lee, *Pitched-Roof PV Mounting: Design and Engineering*

Considerations, in the February/March 2010 issue of *SolarPro* (solarprofessional.com) However, the structural integrity of the system's installation can only be as strong as the structural roof element.

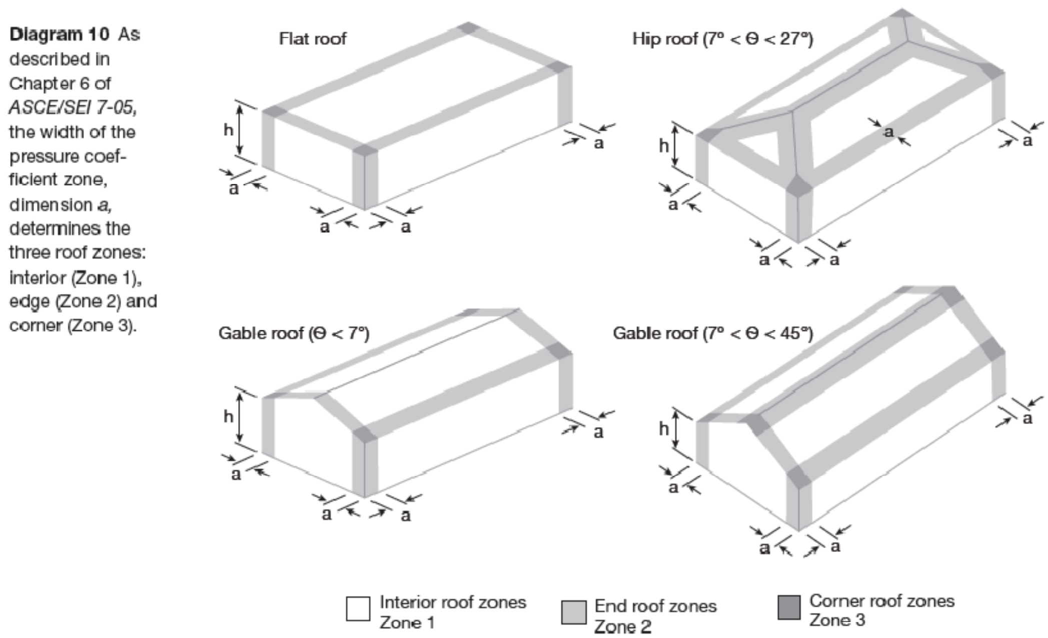

Figure 3: Roof design and location zones per chapter 6 of ASCE/SEI 7-05 (diagram taken from Yun Lee, "*Pitched-Roof PV Mounting: Design and Engineering Considerations*, February/March 2010, *SolarPro*, Diagram 10)

Roof Structure Evaluation

The roof structural elements consist of whatever the array mounting structure is depending on for structural attachment to the building. As will be discussed in the next section, this can be accomplished through mechanical fasteners, ballast or adhesion. The specific requirements for the roof structural elements vary depending on the interfacial attachment type. However, in all cases, the existing or new roof structure must be evaluated for suitability of attachment. As noted in ASTM E44.09 draft WK#21327, the PV system shall not be installed onto damaged (soft spots, droops, unusual discoloration, etc.) structural material—such as roof deck material, rafters or roof support. This work item also specifies that "the condition of the roof structure and surface shall be evaluated to determine whether it is sufficient to meet the design life of the roof-mounted array. Consultation with a roofing professional and building owner is recommended."

NRCA's *Guidelines for Roof-mounted Photovoltaic System Installations*, Section 2.6 Roof Substrate Evaluation, provides an excellent overview of pre-installation inspection considerations, such as expected remaining service life for existing roof systems; roof aging consideration because of integration of the PV system; maintenance accessibility considerations; and guidance for validation of roof design loads and considerations for drainage. It is essential this assessment be performed before even considering installing a PV system on a roof structure.

Critical Interface 1: The Array Mounting Structure to the Roof Structure

Renewable-energy generation meets the building envelope at the interface between the PV array mounting structure and the roof system. For the bulk of the building attachment concerns, this interface is critical, and this is commonly the 'weak link' in the system. The specific requirements for the array mounting structure to roof system interface depend on the nature of the integration; mechanical fasteners, ballast (common for low-slope roof systems) and pressure-sensitive adhesives (typical for low-slope roof membrane systems) claim different advantages and challenges. PV's can be mounted on standing-seam metal roof with nonpenetrating mechanical fasteners attached to the roof seams and, therefore, can avoid the potential concerns with the roof penetration but are limited to the design and size of the seams.

Mechanically Fastened Penetrating Systems for Steep-slope Roofs

Figure 1 provides a representative illustration of a mechanically fastened PV array mounting structure through a tile roof system. The design is unique to tile and is only representative of the issues for other steep-slope roof coverings, since the attachment would differ. The advantages of the mechanical fastening systems are durability and mechanical integrity of the penetrating fastening system. In addition, the mechanically fastened system can be readily accessible for inspection and maintenance depending on design.

A key consideration is that the fasteners must be applied into a roof substrate that is of suitable strength and durability to withstand structural and wind loading requirements throughout the installation's expected life. The ASTM E44.09 draft work item #21327 proposes the following structural requirements for mechanical fasteners when incorporating them into a steep-slope roof system: all fastening should be done into structural members of the roof; the manufacturer of the array mounting structure should report representative fastener installations pull-out values into #1 hem-fir wood substrate per ASTM D1761; and the overall PV array attachment should be designed to resist the uplift loads for a given project, but shall not be less than 30 pounds per square foot. For a given location, the uplift or down load force may vary based on local wind requirements (reference IBC or ASCE 7 for regional and roof zone variations).

The primary concern is preventing water intrusion through the penetration. Therefore, a PV array installer must be trained in the principles of flashings for penetrations in roof construction and weatherproofing concepts for roof systems. Figure 4 provides a side-view illustration for aligning metal flashing with a shingle roof system, which is placed under the roof tile/shingle in correct ship-lap fashion with care not to damage the existing roof covering materials. Figure 5 illustrates this integration from the top view, showing that the flashing must integrate under the tile/shingle at least one full score and into a second score above. These flashing concepts also are illustrated and explained in more detail in NRCA's *Guidelines for Roof-mounted Photovoltaic System Installations*, Section 4.1.

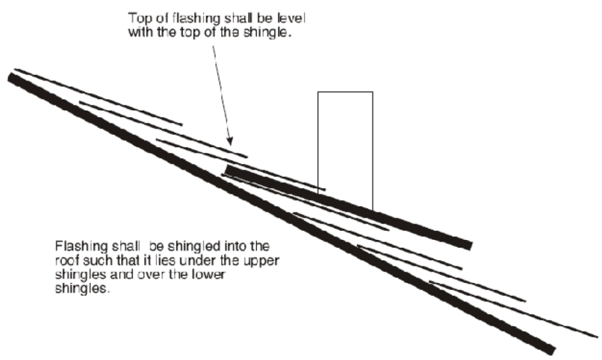

Figure 4: Water-shedding tile **and** shingle configuration for steep-slope roof system**s**

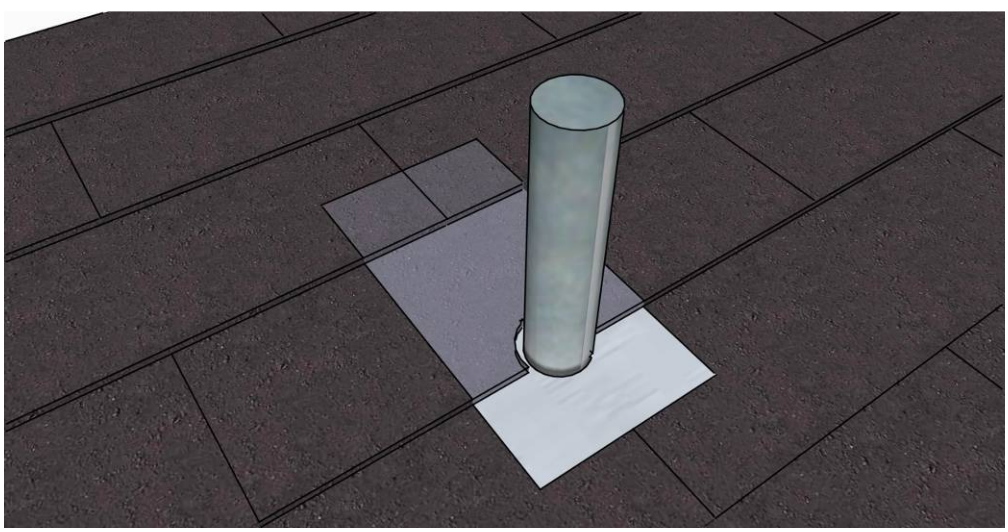

Figure 5: Array mounting structure flashing integration with roof shingles

As previously mentioned, water intrusion is a key performance and durability concern when using mechanical fasteners at this critical interface. Although correct flashing and integration with the roof's water-shedding system should be sufficient to prevent water intrusion though the fasteners, it is essential to test the watertightness of the penetration in case the primary water-shedding protection were to fail. ASTM E44.09 draft work item WK#21327 specifies that "Materials used to flash the fasteners and mounting device to the roof shall be sufficiently durable and compatible with existing roof to maintain this seal through the design life of the installation." In addition, this draft work item requires that the flashing used to prevent water intrusion should meet the water penetration test, ASTM D7349, Protocol 1, using the fastening system used in the array initially and after accelerated aging as specified.

Non-penetrating Low-slope Roof Attachment – Ballasted Systems

A ballasted roof system installation uses ballast, typically concrete blocks, to secure the array mounting structure and meet wind-load requirements. The key advantages are easy and low-cost installation and lack of penetration into the roof, but there are several concerns with this installation method. Specifically, the ballasted "blocks" often are easy to remove from the installation, leaving the PV array mounting structure completely unsupported on the roof and vulnerable to catastrophic wind-uplift failures. In addition, the ballast contributes significant weight to the low-slope roof system and many existing low-slope roof systems are not designed for such additional loads. Structures need to be upgraded to eliminate the possibility of sagging or other structural damage to the roof system, which will result in water ponding and premature deterioration of roofing materials from the standing water exposure. Therefore, it is extremely important that a detailed structural analysis be performed on an existing roof system to determine if structural upgrades are necessary in order to install a ballasted roof-mounted PV system.

For these reasons, among others, NRCA's *Guidelines for Roof-mounted Photovoltaic System Installation* does not recommend the use of ballasted PV systems. Alternatively, mechanical attachment is recommended .

Figure 6: Representative ballasted low-slope roof system installation (picture taken from (http://www.altpowerinternational.com/solar-pv/installations.php)

Fully Adhered Roof Attachment

Adhesive attachment of PV systems to a roof system is most commonly reserved for thin-film flexible PV systems installed directly to a low-slope roof membrane or covering system. The PV laminate typically is supplied in roll form and applied via a pressure-sensitive adhesive on the back of the laminate – Figure 7 provides an illustration. This type of installation offers the advantages of low weight and installation ease with few roof penetrations. However, structural attachment depends on the attachment of the roof membrane to the roof, where mechanically attached roof membranes can have localized ridges or "puckering" that can affect the continuity of the PV attachment system. This may create localized low points that can lead to water ponding, which may result in premature material deterioration. In addition, these adhered low-slope PV systems can be prone to performance reduction caused by the collection of water, dirt, or debris that partially blocks the array's sun exposure. Another concern is the inability to service an existing roof membrane after installing an adhered PV system. In this case, when the membrane reaches the end of its useful service life, the PV system will need to be replaced regardless of the useful service life remaining for the PV. Most importantly, the adhesive system must be of sufficient bond strength and durability to withstand structural load requirements throughout the installation's expected service life. At this time, the author is not aware of any standardized test methods or requirements to measure the adhesive durability and useful service life of this type of attachment system. Therefore, caution is recommended.

Figure 7: Application of a low-slope roof membrane which incorporates pre-laminated flexible PV modules

Critical Structural Component 2: The Array Mounting Structure

The array mounting structure is the structural component that bridges the gap between the PV module framing system and roof structure. In the ASTM E44.09 draft work item WK#21327, the array mounting structure is defined as "All structural and mechanical materials used to support and anchor the photovoltaic modules on the roof system." Specifications for the materials used in the array mounting structure are proposed in the ASTM E44.09 draft standard practice in terms of material durability, thermal resistance, corrosion resistance and flammability considerations. In general, materials used in the array mounting structure are specified such that the expected service life is no less than the design service life of the PV modules. In addition, the Array Mounting Structure must withstand local design loads (including wind uplift, snow, seismic and other dead loads) as defined in applicable local code, or calculated according to ASCE 7 (depending on which is more stringent), including a minimum safety factor. Along with physical property and structural loading requirements, the array mounting structure determines another critical but often overlooked design parameter in PV array installation: the roof-array offset gap.

Implications of the Roof-Array Offset Gap

The roof-array offset gap is the height and distance between the top of the roof system and bottom of the PV array modules. There are a number of performance, durability and aesthetic design implications influenced by the roof-array offset gap, which will be explained in more detail as follows:

Thermal Effect

The roof-array offset gap determines the amount of air flow and ventilation that occurs between the roof covering and PV module framing system/array. This air flow and ventilation contribute significantly to the moderation of temperature gain of the PV module system. Given that the electrical output efficiency of PV modules typically is reduced with increasing temperatures, the degree of ventilation has a significant effect on module output. To illustrate, a crystalline silicone module that has a peak efficiency rating of 18 percent at 25 C (77 F) (standard test condition) may only perform at peak efficiency of approximately14 percent at 65 C (149 F), which easily is reached on a sunny day in a moderate climate zone. In more severe exposure, such as a hot summer day in the southwestern U.S. when roof surface temperatures can reach and exceed 90 C (194 F), the module's peak efficiency can drop to 12 percent, just when the HVAC demand is the highest. This, of course, could result in significant disappointment for the building owner. Therefore, the ventilation provided by the roof-array offset gap is essential to moderating this adverse thermal effect. A larger offset gap results in enhanced ventilation and improvement in the module efficiency performance. This ventilation also will moderate temperature increases on the roof surface, having reduced effects on roofing materials' service life and durability. Conversely, a lower offset gap (less than approximately 50 mm), though providing a more flush, aesthetically pleasing profile on a roof, may exhibit significantly reduced air ventilation and result in higher temperature increases for the PV module and roof system. The adverse effects of a lower roof-array offset gap therefore are reduced module electrical efficiency and service life/material durability concerns for the PV module and roof materials at high temperature exposure.

Also, a real-time field evaluation of the heat effects of adhered PVs on membranes is being evaluated through a study sponsored by the Midwest Roofing Contractors Association (MRCA), Diamond Solar Solutions, Manhattan, Kan., and SRI (www.mrca.org). The MRCA PV demonstration project is collecting thermal data from adhesively applied flex-film PV systems onto low-slope roof membranes made of various materials in Kansas during a three-year test period. Although this will be highly valuable data, only the adhered case is evaluated. Additional field and lab data is planned by the author to further examine the effects of various roof-array offset gaps on efficiency, thermal exposure, and resulting service life/durability of the roof system and PV module/array components.

Effects of Flame Spread

The International Building Code (IBC), Chapter 15, specifies that roof systems be tested for flame spread resistance per ASTM E108, "Standard Test Methods for Fire Tests of Roof Coverings." Per this test method, roof systems are rated for two aspects of combustibility: "flame spread" propagation and "burn through" of a burning brand of specified size. Based on the test results, the roof system is classified as A, B or C, with A being the highest fire-resistance rating. Class A roof systems are common across the U.S . PV modules also are classified with the same fire-resistance rating system per the UL 790 standard, which is based on the ASTM E108 test method. Traditional PV modules typically have a Class C rating. As a result, there is significant interest in the effects of installing a Class C-rated module on a Class A-rated roof system. However, consistent with the theme of this study, characteristics of individual components do not adequately predict the combination of these components as a system.

The Solar American Board of Codes and Standards (Solar ABCs), with support from Underwriters Laboratories Inc., has initiated an industry study to examine the effects of PV module installation on a roof system's flammability classification. At the time the author wrote this paper, this study has not been completed and only preliminary results had been released. However, the preliminary findings present some unexpected conclusions. In summary, it was found that the PV module's actual fire classification did not have the expected effects on the roof system–in fact, the module's effects were not conclusive. It was found that the key determining factor of the fire classification effects on the PV module array-roof system was the roof-array offset gap, where a higher offset gap (greater than approximately 100mm) had a significant adverse effect on the flame spread rating of the module array-roof system. Systems with a lower roof-array offset gap (less than approximately 50mm) or those where the gap was blocked with a noncombustible, non-air-permeable flashing showed a significantly improved flame spread rating–regardless of the module's fire classification. This was explained as a result of air channeling in the gap between the PV module array and the roof system acting to foster flame propagation through the gap. Therefore, the ventilation that has a favorable effect on the thermal performance and efficiency of the PV module-roof system has an adverse effect on the flame spread performance of the same system. This phenomenon results in one of the key unexpected tradeoffs resulting from the critical roof-array offset gap parameter.

Wind Uplift Effect

It is intuitive that a higher roof-array offset gap would result in higher structural/wind load requirements for the array mounting system. However, the calculations detailed by Yun Lee in the February/March 2010 SolarPro article does not include specification of the roof-array offset gap in the structural load calculations, only that this gap height is within a range of 2 inches (51 mm) to 10 inches (254 mm). This also is the case in the draft ICC-ES AC428 specification. Although this may imply that the effect of the roof-array offset gap on wind-uplift requirements is minor—at least within this range—and therefore can be neglected in calculations, it is the author's opinion that this should be further evaluated.

Aesthetic Effect

The aesthetic implications of the roof-array offset gap are significant. The larger gap, which is beneficial to temperature moderating ventilation and access for roof maintenance, is typically considered undesirable from an aesthetics perspective. The lower roof-array offset gap, trending toward zero-gap BIPV systems, tends to have a favorable “integrated” aesthetic appeal, keeping with the profile and design of the building, but can have an adverse thermal and potentially flame spread effect. Therefore, the tradeoffs noted above must be fully considered when determining the roof-array offset gap in the PV system design.

Critical Interface 2: The Module Framing System to the Array Mounting Structure

The interface between the PV module framing components and the array mounting structure typically is specified by the PV module manufacturer or designer and depends on the module framing system design. However, the attachment system, whether it features mechanical fasteners, specialty snap-fit coupling systems or structural adhesive bonding, must be demonstrated to have adequate structural loading strength and durability per the same requirements specified for the other structural components and the array mounting structure-roof interface (per previous discussion).

Critical Structural Component 3: The Module Framing System

The PV module array structure represents the framing elements that give structural integrity and environmental protection to the PV module laminate. The materials used in the module framing system must be selected such that their expected service is no less than the design life of the PV module. Key material property considerations include thermal, ultraviolet, fire-resistance and corrosion resistance. Because a module framing system component is provided along with the PV laminate by the module manufacturer, it often is considered out of the scope of the installer or design professional’s influence. However, the designer must recognize that the module framing system is paramount to the success of the interface to the PV array mounting structure and the physical property requirements and interfacial elements meet the system’s overall structural requirements and durability.

Summary and Conclusions

The growth in installation of PV arrays on roof systems is an exciting new development for the roofing industry, but there are several building science concerns with these systems’ integration into the building envelope. Although there are numerous guidelines providing recommendations for individual aspects of installation, particularly with structural load requirements, the industry needs a comprehensive approach that takes into account the multiple tradeoffs and unforeseen consequences of installation features, such as the various implications of the gap height between the roof surface and PV array. Given that each link in the chain must perform for the entire system to succeed, a detailed assessment of the critical structural components and interfaces involved with the installation is proposed. In addition, field data is essential to better quantify these structural and interfacial performance requirements, tradeoffs and building envelope effects, which is proposed as this study’s next phase of development.

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