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DISCUSSION OF STRATEGIES FOR MOUNTING PHOTOVOLTAIC ARRAYS ON ROOFTOPS

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ABSTRACT

The mechanical attachment of photovoltaic (PV) arrays to rooftops presents a number of unique and challenging issues for system designers and installers. With a resurgence of roof-mounted PV installations due to increasing duel costs and decreasing PV system prices, the Florida Solar Energy Center (FSEC) has accelerated its investigations of array mounting strategies, with the objectives of identifying key performance and cost parameters from a systems engineering perspective. Two principal classifications can be defined for rooftop PV array mounting systems: building-integrated (BIPV) and building-attached (BAPV) or standoff designs. The various attachment methods within these categories each have pros and cons that affect the labor and cost associated with the install and the system performance. An overview and assessment of some existing rooftop PV array attachment methods or mounting approaches, and their advantages and disadvantages with respect to key design criteria are presented to assist designers and installers in the selection of the appropriate method for a given project.

INTRODUCTION

Issues associated with the installation of photovoltaic (PV) arrays on buildings can have a significant impact on initial and overall life cycle costs of these applications, and can range from as little as 10 percent to greater than 40 percent of overall system costs. In the past, most rooftop PV installations required custom-engineered mounting systems, specific to the types of modules, roofing systems and electrical configurations used in a given application. With the recent offerings of prepackaged PV system kits, considerable emphasis has been placed by some on providing universal hardware and installation instructions for mounting PV arrays on different types of roofs. While these methods can be specific to the types of modules used and vary in the types of materials and attachment methods employed, this standardization has assisted in reducing design, materials and labor costs associated with installing PV arrays on rooftops. Those designs that incorporate PV as part of conventional building materials, such as roof coverings, windows and other building components also offer great potential.

OVERVIEW OF DESIGN STRATEGIES

System designers and integrators can be faced with many challenging issues in selecting the optimal mounting strategy for a given application. These issues primarily have to do with the physical and electrical characteristics of modules, and the composition, orientation and structural characteristics of the roof. However, a number of other variables may need to be considered as well. These include effects on the array (and building) thermal and electrical performance, ease of installation and maintenance, and how the PV array electrical circuits are combined and routed to the primary power processing components. Issues associated with the location of equipment and point of interconnection, accessibility, physical protection of the array and safety need to be considered with respect to the array mechanical design.

Two principal classifications can be defined for rooftop PV array mounting systems: building-integrated (BIPV) and building-attached (BAPV) or standoff designs. Building-integrated designs are those considered a functional part of the building structure, or those that are architecturally integrated in the design of the building. This category includes designs that replace the conventional roofing materials, such as shingles, tiles, slates and metal roofing, as well as integral methods where PV modules are used in place of roof decking, windows, skylights, awnings, etc. Building-attached arrays are those considered an add-on part of the building, not directly related to the functional aspects of the structure. These types include rack-mounted arrays and a variety of standoff approaches commonly used in retrofit and new PV installations on buildings.

BUILDING-INTEGRATED DESIGNS

Building integrated photovoltaic modules either displace conventional roofing materials or require no structural attachment hardware. BIPV modules displace conventional roofing materials with PV modules or require no additional mounting hardware that would be required to install the roofing material. BIPV products can come in the form of shingles, tiles, slates, and metal panels. These types of products can be indistinguishable from their non-PV counterparts. Aesthetically this can be attractive if there is a desire to maintain architectural continuity and not to attract attention to the array.

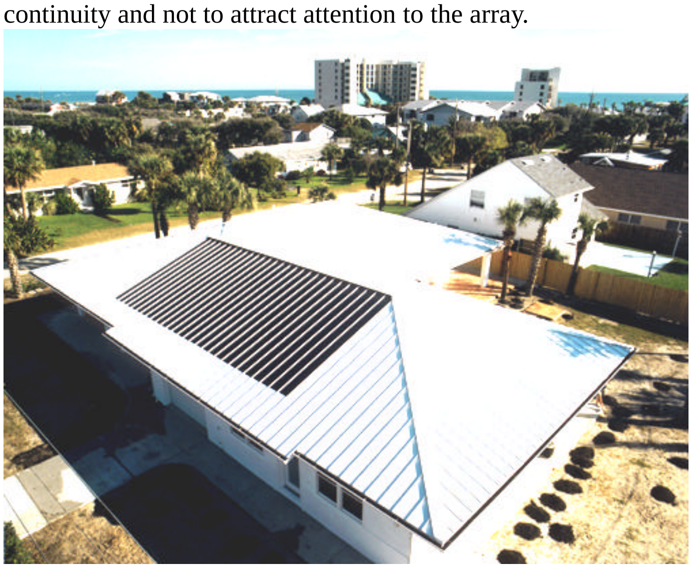

Figure 1. An Example of a BIPV array.

BIPV modules can also be architectural elements that enhance the building's appearance and create visual effects that are very desirable. These types of arrays include custom made module sizes and shapes with opaque or transparent spaces between the cells and can be used for curtain walls, awnings, windows, and skylights.

BUILDING-ATTACHED DESIGNS

Building attached designs rely on a superstructure that supports conventional framed modules. Standoff and rack mounted arrays are the two subcategories for BAPV systems. Standoff arrays are mounted above the roof surface and parallel to the slope of a pitched roof. Rack mounted arrays are typically installed on flat roofs and are fashioned such that the modules are at an optimum orientation and tilt for the application.

Figure 2. An example of a BAPV Array

The superstructure is typically attached to the roof through a series of brackets or 'feet' that are mechanically fastened to a structural segment of the roof system. BAPV arrays can also 'float' over the original roof without any mechanical connection to the roof. In these cases, the array must be ballasted or designed so that it will remain in place when subjected to wind loads or other load that would cause the array to slide, move, or overturn.

FACTORS IN ARRAY MOUNTING SYSTEM DESIGN

Many factors may need to be considered in the design and installation of array mounting systems on buildings, depending on the specific application and products used. These criteria can assist the designer or installer in the selection of the optimal mounting system for most PV building applications, and in identifying areas of concern, opportunities for improvement, and the potential for new products (Barkazi, 1998). Eleven categories of consideration have been identified for consideration in determining the appropriate attachment method for a rooftop PV system. These criteria are:

1. Module Physical and Electrical Characteristics
2. Array Thermal and Electrical Performance
3. Array Orientation, Location and Site Conditions
4. Roofing and Structural-Related Issues
5. Building Thermal Performance
6. Weather Sealing
7. Electrical Integration
8. Installation, Labor, and Maintenance
9. Materials and Environmental Compatibility
10. Aesthetics and Architectural Integration
11. Economic Factors and Costs

PHYSICAL AND ELECTRICAL CHARACTERISTICS

Some of the first considerations in array mechanical design are the characteristics of the modules to be used. Physical characteristics of modules that need to be considered include size, weight, laminate composition, frame type, and mechanical load ratings. Smaller modules with lower output voltage increase the number of interconnections and hardware required for installation of a given size array and nominal voltage. Today, commercially available PV modules are larger than ever before, and this increase in the size and output of the basic building block for arrays has significantly reduced the costs, time and labor associated with PV installations. Due to ever increasing cell sizes, there is a limit on the voltages that can be achieved with crystalline silicon modules of reasonable sizes. The best opportunities for increasing the voltages of PV products lies with thin films and other advanced materials due to the relative ease of laser scribing a greater number of cells in each module. However, their lower efficiency requires greater array area than crystalline arrays of the same power rating.

THERMAL AND ELECTRICAL PERFORMANCE

The effects of temperature on electrical performance and lifetime of crystalline silicon PV modules and arrays are generally well known. Less is known about these same characteristics for many of the newer and advanced thin-film PV products, particularly after several years of exposure. It is assumed that due to the increased degradation potential for materials, the useful life of a PV array is reduced at higher operating temperatures, but to what extent and for which type of PV modules is uncertain. The available field data with current state-of-the-art modules is insufficient to accurately address this issue at present. The twenty plus year warranties now offered by most module manufacturers suggests high confidence in this area, although some have exclusions for higher than normal application temperatures (King, et al, 1998).

The electrical performance of most PV arrays is also strongly affected by temperature, as well as issues associated with the temperature ratings for electrical components. In general, temperature coefficients for power output of crystalline silicon PV arrays reduces by about 5 percent for each 10^o C increase in cell operating temperature. Temperature coefficients for some thin-film and advanced PV materials may be somewhat less. For reasons of electrical performance and maximizing array life, standard design practice suggests minimizing array temperatures wherever possible.

BIPV arrays face the biggest challenges with respect to temperatures, and the performance record has not been particularly good for crystalline silicon products in some situations (i.e. roofing systems). Temperature rise coefficients for these products may be as high as 50 $^oC/kWm^{-2}$. Standoff and rack mounted designs typically operate much cooler, with temperature rise coefficients usually between 15 and 30 $^oC/kWm^{-2}$, which depends largely on the standoff height, array pitch, and openness of the underside of the array (King, 1997). Recent experience with standoff mounted arrays has shown an increase in the temperature rise coefficient by as much as 50 percent for decreasing standoff height from 6 inches to 3 inches (measured from roof surface to top of module).

ORIENTATION, LOCATION AND SITE CONDITIONS

Site-specific conditions ultimately dictate issues associated with PV array installations on buildings. Shading is perhaps the biggest concern due to its impact on overall system performance. Even a small area percentage of shading on an array can have a much greater effect on overall array output. Several external and uncontrollable factors can cause array shading, including trees, nearby buildings, poles, tower and the like. Shading of an array can also be caused by parts of the building on which the array is mounted, and sometimes even from the module or array support hardware. The expected growth of trees and new construction near the array may need to be considered.

General industry practice suggests installing PV arrays with unobstructed solar access window from 9:00 a.m. to 3:00 p.m. solar time throughout the year, because the majority of solar insolation is received during this period. Shading patterns on a potential array location should be carefully evaluated using sun path diagrams for the site before installation.

The tilt and azimuth angles of the array are important factors in performance, and the optimal configuration depends primarily on the site latitude and the seasonal energy performance desired from the system. However, in most cases, the orientation and slope of the roof limit the options for the installer. For most locations in the US, there is little difference in annual solar radiation received on south facing surfaces tilted +/- 15 degrees from latitude. Although there are variations in amounts received during certain season – the lower tilt surfaces receive more insolation in summer months, the greater tilt surfaces receive more in winter. While west-facing arrays produce less energy than south facing arrays, they can help offset demand for afternoon peaking utilities.

ROOFING AND STRUCTURAL-RELATED ISSUES

One of the more important issues in the design of PV arrays on buildings is the structural attachment of the array mounting system to the roof surface and structural members. The PV array may encounter several types of loading on a rooftop. The design of the modules and mounting system must withstand these forces and comply with applicable building codes and standards. Primary load types include dead loads and live loads. Dead loads are static and due to the weight of the array and support structure. Dead loads are typically minimal, no more than 5-10 lbs/ft^2. However, the loads are often transferred to the rooftop through mounting devices that concentrate the array dead loads onto small surface areas of the roof or individual load bearing members. These conditions can significantly add to the loading conditions of a single truss, rafter, joist, decking or other roof component. Live loads can be large in magnitude, but are intermittent, and attributed to wind, snow, etc and maintenance personnel. Most PV modules are rated for static loading of 50 -55 lbs/ft^2, or equivalent to the pressure of constant 110 - 120 mph winds acting normal to the module surface.

The location of roof brackets or mounts may depend on the dimensions of the panels or subarrays and may not coincide with locations of structural members. In these cases, direct attachment to the roof decking is often used, but the strength and reliability of this approach is questionable. It is strongly recommended to attach mounts to a roof truss, rafter, purlin, or joist rather than to the roof deck alone when high wind-induced loads are anticipated.

The possible need for re-roofing within the lifetime of PV arrays presents another variable to consider with the design or array mounting systems. For example, common fiberglass shingles have expected lifetimes of less than twenty years, while the economics associated with a PV system are generally computed over a period in excess of 20 years. The costs associated with the removal and reinstallation of the array at least once during the life of the system is rarely considered in any payback calculations.

BUILDING THERMAL PERFORMANCE

PV arrays installed on buildings can have positive and negative impacts on the heating and cooling loads of buildings, but these are often overlooked as part of array mechanical design. Direct and integrally-mounted arrays often have the greatest effect on increasing heat transfer between the roof surface and conditioned spaces, which can be to an advantage in cold climates, but a disadvantage in warm climates where air-conditioning loads dominate. Well-ventilated and large attic spaces with adequate insulation can moderate the heat gain into buildings from these types of arrays, however the principal heat transfer mechanism is generally radiation from the underside or the roof (array) surface to the top of the insulation. Radiant barrier materials applied to the underside of the roof surface can be used to reduce this radiation component. However, this can cause a slight increase in module temperature that will reduce the PV system electrical performance. Standoff mounted arrays typically do not increase heat gain to the building, and in most cases, they reduce roof temperatures by shading the roof from direct solar gain. Reduced roof temperatures translate into less conduction heat transfer through the roof section, thereby lowering temperatures of the roof underside and corresponding radiation heat transfer to the top of conditioned spaces (Barkasz1, 1998).

WEATHER SEALING

Weather sealing of array mounting attachments and roofing penetrations is a critical issue for PV array installations on buildings. In addition to obvious problems associated with leaking roof penetrations, water entering through or around a roof penetration can weaken the roof substrate and compromise the structural integrity of the array attachment. The physical damage to the roof can occur long before the leak is visible or before cosmetic damage occurs.

Although accepted roofing industry practices are used in weather sealing many rooftop PV installations, many more use methods that may function initially, but are likely to degrade over the life of the system. Notwithstanding re-roofing issues, weather sealing of PV array attachments and penetrations through buildings should meet or exceed the lifetime expectations for the system. Many array attachment methods use a bracket or mount that is directly attached to the roof decking or to a structural member with mechanical fasteners. Typical practice is apply a long life, UV resistant butyl rubber or elastomeric caulk or tape to the underside of these brackets and to the tops of fastener heads during final assembly. While this is a quick, simple and low-cost approach, a better practice is to flash around the brackets, or made easier using some type of cylindrical post over which the top of the flashing or boot may be clamped and sealed to the post. Careful attention should be paid to brackets that may dam water and debris behind them, which may lead to seal failure and leakage. In any event, good design practice suggests limiting the number of roof attachment points and penetrations to the minimum required to meet structural and array loading requirements (Dunlop et al, 1999).

ELECTRICAL INTEGRATION

Of the more challenging issues facing building-integrated product are those associated with integration and compliance with electrical building codes.

Temperature, outdoor exposure and sunlight effects require high 90?C plus temperature ratings to be used for all array-related electrical components, including wiring, conduit, junction boxes and terminations (NFPA, 1999).

INSTALLATION, LABOR, AND MAINTENANCE

Preferably, the installation of PV arrays on standard types of roofing should not require excessive site-specific information or detailed structural drawing of the building. If the array is to be installed as part of the construction of a new building, the PV contractor can easily coordinate with the other subcontractors to facilitate the installation. For retrofit applications, array mounting systems must be flexible enough in design to accommodate various field conditions or application specific hardware must be provided.

While properly installed PV arrays should require little or no maintenance and the objective for any contractor is not to have ‘call-backs’ to a job, problems do occasionally arise. The problem may not be with the mounting system but may in fact be with an electrical component. The mounting system must be designed to allow for servicing the array or components with ease. Tilt-up panels or individually removable modules make service and troubleshooting a problem quicker and less costly.

Figure 3. A BAPV Array Featuring a Tilt-up Mounting System

MATERIALS AND ENVIRONMENTAL COMPATIBILITY

Materials issues are at the heart of any mechanical design, and in the case of mounting PV arrays on buildings, should be considered with respect to the environment, and lifetimes of the array and building components. These issues are complicated by the fact that PV arrays are installed in a wide range of locations with varied conditions. Principal concerns are associated with corrosion, in hot, humid and salt air climates. For example, PV array mounts used in coastal areas of Florida have degraded significantly more than similar designs in the western United States. The use of standard plated fasteners, steel support structures, and direct contact between dissimilar metals have often been the causes of this accelerated degradation of array mounting components. Corrosion resistant stainless steel fasteners (types 316 and 403) and structural aluminum (types 6061 and 6063) are often used to minimize corrosion of these components, however the aluminum must generally be insulated from contact with stainless fasteners to prevent limit corrosion. Direct contact between aluminum and concrete should also be avoided for similar reasons. EPDM or butyl rubber materials can be used in many instances to isolate components from coming into direct contact with one another. An anti-seize compound may also be applied to threaded fasteners to retard corrosion. Furthermore, all array mounting components, (particularly electrical components) should be rated for extended UV exposure and sunlight resistance. Mounting materials must also have the appropriate class fire rating for the intended application, which may be addressed as part of equipment listings and local building codes.

AESTHETICS AND ARCHITECTURAL INTEGRATION

Although aesthetic features of PV array installations on buildings have little to do with the functionality, performance and lifetime of arrays, they have much to do with public acceptance of PV technology in general. Whether a given application uses building-integrated or building-attached designs, there are a number of architectural principles that may be applied to the design and installation of arrays on buildings that can improve appearance and acceptance. One basic principle is to ensure that the lines and location of the array are consistent with the building features. Unless there is the potential for significant gains in performance due to orientation and shading issues, arrays should be mounted parallel to the roof surface, and centered and square with respect to the rooflines and edges. An obvious exception would be flat rooftops where rack type arrays would typically be used. The color of a PV array is often a noticeable feature, as are the reflections and glare from the array surface. While the color of PV arrays is generally limited by the specific materials technology, there are considerable options ranging from red to gray to bright blue. When possible, harsh contrasts and patterns should be avoided. The color of building features can also be adjusted to better match and blend with the colors of the array. Although not often a major problem, reflections and glare can cause annoyances and even serious safety issues for some installations, which can affect nearby buildings, persons, local traffic, and even aircraft. However, these occurrences are typically limited to specific times of the day and year, and when the sun is low in the sky. Where reflection issues are a concern, the designer must evaluate solar incidence angles to determine the angle of reflection for the given applications at all times of the day and throughout the year. The location of array support structures, hardware, and electrical wiring, conduit and junction boxes are another major consideration. These items should be as inconspicuous as possible, neatly tied or concealed beneath the array. The routing of conduits or conductors from the array to the power processing components should also be as streamlined as possible, especially where it transitions through the roof or eave of the building (Strong, 1994).

ECONOMIC FACTORS AND COST

At present, the mechanical design and installation of PV arrays on buildings may be the largest variable from the installer's perspective, and may have the largest variability in overall system costs for PV installations in general. Custom, site-specific designs unquestionably are major cost drivers for PV installations, suggesting the use of standard designs and techniques wherever possible.

Simple to install and removable arrays are an attractive feature when it comes to re-roofing considerations. In addition, many homeowners do not remain in their homes for 20 years of more. Since this is the expected lifetime of the system, a homeowner may not wish to leave such a sizeable investment with the home if they relocate.

OPPORTUNITIES FOR COST REDUCTIONS AND IMPROVEMENT

The further reduction of costs associated with the installation of PV systems can be accomplished in many ways. As new homes are being constructed or existing homes are remodeled, the additional bracing for the physical attachment of the array can be installed and the electrical system can be pre-wired for a PV system. This work can be completed for a fraction of the labor cost that would be required in a retrofit situation. The standardization of balance of system (BOS) components, electrical connectors, etc can minimize the need for custom or site specific designs. Lower cost, yet durable, framing systems or frameless modules can not only reduce materials cost but can increase installation options. The development of larger and higher efficiency modules can decrease the installation labor. There is still much room for improvement and simplification in the pre-assembly of BOS components, wiring, and mounting hardware.

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