Introduction

Rooftops are an ideal location for photovoltaic (PV) modules. Roofs typically have exposure to abundant sunlight, the building framework offers a robust structure for PV module securement, and high-voltage equipment can be located away from public access. Roof-mounted PV arrays convert an otherwise unused space into one that generates non-polluting solar electricity at the very location where that electricity will be used. This is far more efficient than transporting electricity from large power plants across hundreds or thousands of miles to end-users. Over the past decade, this distributed generation strategy has become increasingly important to utilities.

There are an estimated 11 million square feet of PV modules installed on rooftops in the U.S. today, approximately 60% of which are installed on sloped roofs, and the remainder on flat roofs. As roof-mounted solar arrays become more and more popular, it is important for the roofing and solar industries to become better acquainted with one another. Solar experts installing arrays on rooftops need to collaborate with experienced roofers, and roofing experts need to become familiar with the roofing issues that should be considered with roof-mounted solar arrays. A solid partnership between the solar and roofing industries will ensure that roof integrity is maintained and that PV performance is optimized. This paper presents a brief introduction to solar technology, and a discussion of the roofing issues that should be considered with roof-mounted PV arrays.

PV Basics

Most PV modules used in roofing applications are composed of groups of crystalline silicon solar cells encapsulated in a clear, UV-resistant plastic to protect the cells from moisture in the environment. The encapsulated solar cells are sandwiched between a top layer of tempered glass and a back layer of plastic film. This construction is similar to safety glass used in automobile windshields, and is similarly very resistant to impact from objects such as hail.

PV modules often employ an aluminum frame to provide a means of attachment to a structure. Frameless crystalline PV modules are also commonly used, in which case adhesives are used to bond the PV module to a support structure. Most PV modules come with a 20- to 25-year manufacturer warranty.

Other types of PV modules are commercially available, but currently make up a smaller part of the PV market. Recent developments in amorphous silicon solar cells, fabricated with either a glass or flexible plastic top surface, and non-silicon PV cells such as those made of cadmium telluride, may give rise to an increased market share for these technologies.

PV modules generate direct current (DC) electricity. In order to be used with most appliances and to be compatible with utility power, an inverter is used to convert the DC into alternating current (AC) power. There are many types of inverters that can be used with a PV system, depending on the application. An experienced solar contractor should be consulted to specify this critical component.

Roof-mounted PV systems have historically been used in remote locations where utility power was unavailable. These stand-alone applications require that solar energy be stored in batteries so that power is available to the building at night and on overcast days when solar power is not present. Independence from utility providers is the advantage of using batteries, while the disadvantages are the required maintenance and cost.

Today, grid-tied systems are increasingly popular. Grid-tied systems consist of PV modules, an inverter, and miscellaneous components such as wiring, mounting hardware, electrical boxes, disconnects, and fuses. The AC power from the inverter is connected directly to the utility grid. When the system generates more power than is being used at the site, the excess power can flow to the utility, turning the utility meter backwards. If there is not enough solar power being generated to meet the building’s demand at any time, power flows from the utility. Because utility power is available as a backup source of power, no batteries are required for energy storage.
Applicable Codes and Certification Requirements

PV modules used in roofing applications must be listed by Underwriters Laboratories (UL) under the UL standard 1703. This standard requires that modules undergo structural, fire, and electrical testing such as resistance to hail, ultraviolet light (UV), thermal cycling, humidity, mechanical loading, fire, and high voltages.

The UL 1703 evaluation includes a high-voltage test that qualifies the modules for use at voltages up to 600 volts (DC).

Most PV modules are also certified under international standards such as the International Electrotechnical Committee (IEC) 1215, and the Institute of Electrical and Electronics Engineers (IEEE) 1262. Although these test standards are similar to UL 1703, the lack of one harmonized international test standard means that PV manufacturers are required to qualify their product through three different test programs.

The UL, IEC, and IEEE standards for PV do not address roof-specific issues such as the waterproofing of roof penetrations or the structural integrity of the PV-to-roof securement. In the future, PV modules and mounting systems may be certified by Factory Mutual (FM), the International Code Council (ICC), or other agencies to facilitate permitting and obtaining adequate insurance for the building and the system. Some PV manufacturers are currently working with these agencies to develop performance criteria. To date, reaching an agreement on performance criteria for a product with a unique combination of electrical, structural, and roofing design issues has only been accomplished on a case-by-case basis for each type of mounting system.

To ensure electrical safety at the system level, the electrical design must comply with the National Electric Code (NEC) and local building codes that are applicable to the particular site, such as the International Building Code (IBC).

To guarantee that PV systems are code-compliant, safe, and reliable, only qualified professionals should oversee the design and
installation. A roof-mounted PV installation requires a unique combination of electrical, structural, and roofing skills, as well as a thorough understanding of how PV systems operate. Licensing requirements for solar installers vary from state to state; in some states, a special solar contractor’s license is required, while in others a general contractor’s license or electrical contractor’s license will suffice. Check with the local building department to determine the licensing requirements within a particular state.

Types of PV Roofing

PV modules can be installed on flat or sloped roofs as shown in the accompanying photos. Modules may be mounted in the same plane as the roof (Figures 1 and 2), or may be inclined relative to the roof surface (Figures 3 and 4).

For applications in the northern hemisphere, the output of the solar panels is optimized when the modules are sloped toward the south by an inclination angle that is approximately equal to the latitude of the building site. When modules are sloped relative to the roof surface, a shadow is cast to the north of the modules; therefore, adequate space must be maintained between rows of modules to minimize energy collection losses due to shading (Figure 3). The effect of shading on power output can be significant - a small area of shading on a single module will reduce the output of an entire group of modules that are wired together in series. If modules are installed in the same plane as the roof surface, shading is not an issue and the modules can be placed side by side with no space in between them.

To maximize the solar power generated for a given roof area, modules should be installed flush to the roof surface to obtain the maximum power density. If more than enough space exists for the desired solar array, sloped PV modules should be considered with an adequate spacing between rows of modules in the north-south direction.

Various mounting techniques are used to secure PV modules to sloped roofs.

1. Rack-mounted systems incorporate structural components and mechanical fasteners to secure the PV module to the roof (Figure 5). This securement option has the advantage of conforming to standard roofing practices that are familiar to the customer, contractor, and building officials, thereby facilitating the design and permitting processes. Rack-mounted systems elevate the module off the roof surface, which helps to reduce the module tempera-
The SunTile™ PV roofing system has a Class A fire rating and a 110 mph wind rating from UL. Pre-engineered design guidelines can improve aesthetics and save time and money for designers and installers compared to custom-designed rack-mounted systems. Photo courtesy of PowerLight Corporation, Berkeley, CA.

Figure 6 – The SunTile™ PV roofing system has a Class A fire rating and a 110 mph wind rating from UL. Pre-engineered design guidelines can improve aesthetics and save time and money for designers and installers compared to custom-designed rack-mounted systems. Photo courtesy of PowerLight Corporation, Berkeley, CA.

Figure 7 – Amorphous-silicon PV modules adhered to standing seam roofing panels on a sloped roof. Photo courtesy of PowerLight Corporation, Berkeley, CA.

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Another option for securing modules to sloped roofs is a modular mounting system integrated with crystalline modules. SunTile™ Roof Integrated Systems, manufactured by PowerLight Corporation, is an example of this type of roofing system (Figure 6). These PV roofing tiles are available with pre-engineered design guidelines, including a wind and fire rating from UL. These roofing tiles are compatible with common roof types such as asphalt shingles, concrete S-tiles, and flat concrete tiles. The clean, integrated appearance is an aesthetic improvement over rack-mounted systems. Some products in this category, such as SunTile™, are designed to promote natural convective cooling on the module back surface to reduce the module temperature and heat gain into the building.

3. A third option for securing modules to sloped roofs is the “PV shingle,” a flexible plastic PV module made with amorphous silicon PV cells. This product is nailed to the roof deck in an overlapping fashion, like an asphalt shingle, and can be used in conjunction with asphalt shingles. The advantage of the PV module is that it can be installed without penetration cuts through the roof membrane. Some products, such as SunTile™, are designed to promote natural convective cooling on the module back surface to reduce the module temperature and heat gain into the building.

The disadvantage of rack-mounted systems is that they require numerous penetrations through the roof membrane. Installing and waterproofing the structural attachments can be labor-intensive, and can be a source of anxiety for the customer and the contractor.

Another rack-mount disadvantage is that each system must be custom designed, increasing the labor cost for the installer. Rack-mounted systems can also suffer from poor aesthetics. Despite these disadvantages, this type of mounting system is currently the most common method of securing modules to sloped roofs.

1. Roof membranes are commonly asphalt shingles, concrete S-tiles, and flat concrete tiles. The clean, integrated appearance is an aesthetic improvement over rack-mounted systems. Some products in this category, such as SunTile™, are designed to promote natural convective cooling on the module back surface to reduce the module temperature and heat gain into the building.

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Figure 9 – PV modules integrated into the roof of a residential building. Photo courtesy of Solar Design Associates, Harvard, MA (www.solardesign.com).

shingle is that it uses standard roofing practices and has an integrated appearance, which is aesthetically pleasing to both builders and homeowners. One disadvantage of this technology is that the lack of an air space behind the modules results in a higher operating temperature, which may decrease the module efficiency, as well as transfer heat directly through the roof deck. In addition, the amorphous silicon technology, which allows the shingle to be fabricated into a flexible module, has a lower efficiency, about 7% as opposed to 13-20% offered by the crystalline solar cells. A lower-efficiency module will require more area to generate the same amount of electricity as higher-efficiency modules. The impact of using lower-efficiency modules on the economics of the project should be evaluated on a case-by-case basis.

4. There are other types of PV roofing designs for sloped-roof applications. For example, flexible amorphous silicon modules can be laminated to standing-seam metal panels (Figure 7). For standing-seam roofing applications, custom clamps can be used to attach the PV structural components to the metal seams (Figure 8), just as snow guard products are attached to metal roofs. Finally, crystalline modules may be used in place of traditional roofing materials (Figure 9). This option is generally only feasible for new construction projects, and waterproofing details would need to be custom engineered for each particular building.

For flat roofs, the three securement options are rack-mounted, ballasted, or adhesive-mounted PV systems. With rack-mounted and ballasted options, sloped or flat modules may be used, depending on the desired power density. Sloped modules have a higher output per module, but require more space. Since flat-mounted modules do not shade each other, more power per square foot of roofing is achieved. Adhesive-mounted PV roofing systems consist of a flexible plastic amorphous silicon panel adhered or laminated to a single ply roof membrane that follows the contour of the roof.

Rack-mounted systems on flat roofs follow the same approach as with sloped roofs, except that the waterproofing of penetra-
lations will vary with the type of roofing material. A rack-mounted PV system with inclined modules is shown in Figure 10, and a similar system with horizontal modules is shown in Figure 11. Specifications for waterproofing should be based on roofing manufacturers’ recommendations.

Ballasted systems have become the most common way to secure PV modules to flat roofs. This type of system is kept in place on the roof deck by means of its own weight, as well as its aerodynamic design. The lack of lateral gravitational forces on flat roofs limits the governing forces on the array to wind and seismic loads. Four types of ballasted PV systems are shown in Figures 12 through 17. Figures 12 and 13 show a design that incorporates a framed, sloped PV module into freestanding metal supports.

Figures 14 through 17 show flat and sloped PowerGuard® tiles manufactured by PowerLight Corporation. Here, flat or sloped frameless PV modules are attached to extruded polystyrene foam with a tongue and groove connection (Figure 14). An air gap separates the PV from the foam to promote cooling of the module, and the foam layer reduces heat flow into the building. This technology has emerged as the leading mounting option for flat, commercial roofs, with over 2 million square feet installed in the U.S. alone.

Ballasted systems must be properly designed and installed to ensure that they will withstand wind, seismic, and thermal loads. In addition, ballasted systems may be incompatible with some types of roofing systems. These issues are discussed in more detail in the following two sections.

Adhesive-mounted systems are a relatively new product on the market. The clear advantage of this type of product is the low-cost and simple installation. The low efficiency and heat transfer to the roof deck are the disadvantages. A technical challenge for this product might be to withstand ponding water when installed on near-flat roofs.

Structural

Structural loads on PV arrays include forces from wind, gravity, thermal expansion, and earthquakes.

Two approaches are commonly used in the solar industry to address wind loads on PV systems. Building codes are often used to calculate wind uplift loads on roof-mounted modules using the same methods used to design roofing systems. The International Building Code (IBC) or the
flow reduces wind loads in ways not predicted by codes.

In place of codes, wind tunnel testing in accordance with ASCE 7-02, Section 6.6 is currently the only recommended method of determining the actual wind resistance on a PV array. Although computational fluid dynamics (CFD) software and other analytical techniques are often a part of a wind tunnel test program, at this time these techniques cannot accurately predict the complex and dynamic wind flow on top of a roof.

Whether wind tunnel testing or building codes are used to determine wind loads on modules, it is important to consider the nature of wind loads on roofs and roof-mounted equipment. For example, wind loads are highest at the corners and edges of the roof. If PV modules are placed in the corner or edge regions of the roof, additional securement may be needed. The array should be located as close to the middle of the roof as possible to reduce wind loads on

American Society of Civil Engineers Minimum Design Loads for Buildings and Other Structures (ASCE 7-02) can be used to determine wind loads on a PV array.

Another approach is to determine wind loads based on analysis or testing. This is commonly done when it is believed that the modules will experience lower wind loads than predicted by the code. Ballasted systems always follow this alternative approach, because it would not be feasible to make the system heavy enough to withstand wind uplift loads predicted by codes. Since most PV systems have gaps between adjacent modules, the permeability to air flow reduces wind loads in ways not predicted by codes.
and should be considered as an additional dead load on the roof. Structures must be verified as possessing adequate roof loading capacity to handle the extra weight of the PV system.

Special attention should be paid to roof loading during the installation process, especially with larger PV projects. Heavy pallets and packages of materials are typically lifted to the roof by cranes, and then broken down and moved into place. This aspect of the installation requires careful planning to avoid overloading the roof.

Thermal expansion of materials can also create substantial forces on arrays and the roof. This is especially important to consider with large arrays mounted on steel or aluminum structural components, and those with long conduit runs. Standard analytical techniques should be used to ensure that thermal expansion and contraction of PV components will not result in damage to the PV system or the roof.

Roofing

Before a PV system is installed on a roof, the roof should be inspected by a qualified roof inspector to ensure that the roof is in good condition. Often, simple repairs to the roof that will extend its life and prevent leaks can be made before installation. A moisture survey and core sample are often recommended to determine if the layers of the roofing system are in good condition. If the roof insulation has been damaged by moisture, the weight of a PV system placed on top of the insulation could easily exacerbate the situation.

Special attention should be paid to existing roof membrane penetrations. Solar panels may be mounted around (or sometimes over) penetrations. An 8-12’ minimum flashing height above the membrane is recommended for rack-mounted systems. The integrity of the sealing system around penetrations should be investigated by a roofing inspector. Access requirements to existing penetrations and/or roof-mounted equipment should be considered when planning the array layout.

The age of the roof should also be considered before installing a PV system. If it is expected that the roof will need replacement in less than five years, it may be more economical to replace the roof before installing the system, as opposed to re-roofing around the system or removing it while the roof is replaced. Installed properly, some PV products can extend the life of the roof. For example, PV products that fully cover and/or insulate the roof will protect the membrane from high temperatures and UV exposure – the leading causes of roof degradation.

Accessibility of the roof surface should be considered if coatings need to be reapplied periodically, such as the elastomeric coatings used with spray-foam roofing.

PV systems require very little maintenance; therefore, foot traffic is typically not an issue. Exceptions to this may be with large systems, which may see heavy foot traffic during installation, or with systems that are visited frequently for educational or other purposes. In these cases, temporary or permanent precautions for protecting the roof from foot traffic should be considered.

Roof-mounted systems should be designed to work with the existing drainage system of the roof to ensure that the roof will continue to drain properly after installation. Otherwise, modifications to the drainage system should be made so that...
With ballasted single-ply membranes, a ballasted PV system may be installed over the existing gravel or pavers if wind tunnel studies demonstrate that the added air volume under the PV system (contained in the voids in the gravel or pavers) will not reduce the wind performance of the system to an unallowable level. The additional weight of the array over the gravel should be confirmed to be compatible with the membrane below. The preferred approach is to remove the gravel from the roof before installing a ballasted PV system. If the roof ballast is removed, a wind expert should verify that the membrane remains adequately ballasted by consulting the guidelines published in the document ANSI/SPRI RP-4, published by the American National Standards Institute and the Sheet Membrane and Component Suppliers to the Commercial Roofing Industry.

Some types of roofing may be incompatible with ballasted systems. Mechanically attached, single-ply roof membranes that do not have an adequate air barrier may be prone to billowing. Ballasted systems typically do not weigh enough to remain in place if the membrane billows. Roof consultants and individual roofing manufacturers should be consulted to determine if membrane billowing could be a potential problem.
Electrical Safety and Grounding

The NEC requires that all accessible metal components in a PV array be electrically bonded to earth ground. A ground wire must be properly connected to the frames of PV modules, and the entire system bonded to a common ground. Manufacturers of framed, UL-listed PV modules provide instructions on achieving a proper ground between modules. When PV modules are installed on metal roofs, it should be verified that each metal roofing panel in the proximity of the PV system wiring is electrically bonded to earth ground. It should not be assumed that each discrete panel is electrically connected to adjacent panels, or that the metal roof itself is grounded. A qualified electrical engineer should verify the electrical design of the PV system to ensure that the system is properly designed and adequately grounded.

Conclusions

The solar industry is growing rapidly in the U.S. and abroad. Utilities are in need of reliable electricity production in urban centers, where the demand is located. Domestically produced, non-polluting and sustainable sources of electricity are required to ensure the health and security of future generations. Rooftops are clearly an ideal location for PV arrays, but, as a critical component of the building, roof-mounted arrays need to be carefully designed and installed. Roof consultants are encouraged to view this rapidly growing approach to roof utilization as a business opportunity as well as a chance to make a positive environmental change. Collaboration among the solar industry, roofing industry, and building officials is essential to ensure that the PV and roofing systems perform reliably and safely over their intended design life.

Colleen O’Brien

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